

Chapter 1. Introduction

1.1 Rationale

Soil organic carbon (SOC) plays a key role in determining the physical, chemical and biological properties of soil. Maintaining or improving SOC stocks is fundamental to sustaining crop productivity. 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 the 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 (Henderson and Bishop 2000, Bond and Grundy 2001, Chirinda *et al.* 2010). Such cultivations are known to break soil structure and aggregates, exposing the physically protected soil organic matter to microbial attack, thus stimulating the release of CO₂ to the atmosphere (Angers *et al.* 1993, Six *et al.* 1999, von Lützow *et al.* 2006). Despite requiring multiple cultivation operations, the vegetable systems are also characterised by little or no crop residue input (Jackson *et al.* 2004, Chan *et al.* 2007), potentially further reducing SOC stocks in soils used for vegetable production. In the light of this, sweet corn, a relatively high value vegetable crop, was proposed as a rotation crop for a vegetable system so that there would be an excess of residue available as input to soils.

Therefore, the effect of corn residue incorporation on SOC in two soil management systems (SMS; i.e. organic and conventional) was examined as an alternative to the removal of residue because such a practice may be an option to counteract the loss of C due to multiple tillage operations that vegetable systems, especially organic ones, routinely use (Henderson and Bishop 2000, Bond and Grundy 2001, Chirinda *et al.* 2010). The term ‘alternative’ in the thesis is used to describe either an organic SMS as an alternative to conventional systems or residue incorporation in soil as an alternative to residue removal from the fields or both.

1.2 Thesis aims and research questions

The principal aim of this thesis was to examine the effect of sweet corn residue management (RM; i.e. incorporation or removal) in the two SMS on soil carbon (C) concentrations and stock, total organic C (TOC) fractions and microbial biomass C (MBC) through a field experiment. A laboratory experiment was performed to separate confounding factors in the field experiment. Another laboratory trial was conducted to supplement the field experiment where the effect of residue incorporation and simulated tillage on the emission of CO₂-C and TOC fractions was studied. Although, the research objectives about this thesis are focused on SOC, agronomic and fertility parameters, which are the essential components of a crop production system, were also considered. Therefore, the major objectives of the thesis were:

1. to examine the effect of RM (incorporation or removal) and SMS (organic and conventional) on yields of and nutrient uptake by sweet corn residue and cabbage head and on soil nutrients. This objective includes an evaluation of the sequestering of atmospheric CO₂-C as corn residue, whose effect on SOC parameters are explored by the following objectives,
2. to examine the effect of RM and SMS on the TOC concentration, SOC stock and MBC,
3. to further examine the effect of these treatments on the labile (particulate organic C and dissolved organic C) and stable (mineral-associated organic C) fractions of TOC, and
4. to examine the effect of two potentially opposing determinants of TOC, residue incorporation and simulated tillage (the surrogate for cultivation), on the emission of CO₂-C and TOC changes.

1.3 Thesis structure

This thesis is divided into seven chapters. A brief overview of each chapter, along with how they are linked together, is presented here.

Chapter 1: Introduction. This chapter provides a brief rationale, states the research objectives and outlines the organisation of this thesis. All field and laboratory experiments of this thesis were conducted on Vertosol and Chromosol, the two common agricultural soils in Australia. These soils have contrasting chemical and physical properties, but also occur in close

proximity at the University, allowing field trials to be conducted without confounding climatic effects.

Chapter 2: Literature review. This chapter provides a general review of the literature on SOC; however specific literature relevant to a particular chapter may be repeated in the experimental chapters concerned as this thesis is presented in a journal article format.

Chapter 3: Influence of corn residue incorporation in organic and conventional soil management systems on the yields and nutrient uptakes by sweet corn and cabbage, weed biomass and soil nutrients. This chapter investigates agronomic and soil fertility aspects influenced by RM and SMS. Corn and cabbage yields, and nutrient uptake by corn stover and cabbage head are examined and the effect of the treatments on soil nutrients and structural stability are evaluated. The role of residue incorporation in suppression of weed biomass is also assessed. As corn residue is the important component of this thesis, atmospheric CO₂-C sequestered in the form of biomass is also examined in response to the RM and SMS treatments.

Chapter 4: Effect of alternative cropping management on soil carbon concentration and stock, and soil microbial biomass carbon. This chapter describes the testing of the hypothesis that if corn residue incorporation and application of organic fertilisers could counteract loss of SOC due to tillage in a vegetable production system. The objective was pursued in a field trial where the effect of corn residue incorporation in a corn-cabbage rotation using organic and conventional SMS on TOC concentration, SOC stock and MBC were studied over two years (four cropping seasons). In addition, a laboratory experiment was conducted to separate confounding factors of the SMS in the field experiment – i.e. the use of herbicides and mineral fertilisers in the conventional SMS and the use of cultivation and organic fertilisers in the organic SMS.

Chapter 5: Effect of corn residue incorporation and soil management systems on soil carbon fractions: Results of field and laboratory experiments. This chapter follows on from Chapter four to further study the effect of treatments on the TOC fractions to determine the form which the C accumulated in soil via residue and organic fertiliser or pre-existing C eventuate. The chapter explores the effect of treatments beyond TOC concentration and provides deeper understanding of soil C dynamics in different forms. The labile fractions of particulate

organic C and dissolved organic C, and the stable fraction of mineral-associated organic C were studied using soil samples from the field and laboratory incubation experiments.

Chapter 6: Soil Carbon changes and CO₂ emissions due to incorporating corn residues and simulating tillage – A laboratory study. To narrow the focus further, this chapter focuses on how two potentially opposing determinants of TOC, residue incorporation and simulated tillage, influence the emission of CO₂-C. Specifically, the research in this chapter studies whether or not the incorporation of residue is sufficient to counteract the loss of C due to tillage (soil disturbance). This chapter completes a cycle of investigation from the sequestering of atmospheric CO₂-C in the form corn residue, followed by its application in soil for the formation of TOC and its fractions, to finally examining the effect of simulated tillage and residue incorporation on the release of CO₂-C back to the atmosphere.

Chapter 7: Conclusion. The final chapter synthesises the key findings with respect to the research questions, identifies implications, and outlines the limitations of the research and makes recommendations for future research directions.

Chapter 2. Literature review

2.1 Introduction

2.1.1 Soil carbon and its importance

Soil organic carbon (SOC) is the part of carbon (C) in the soil that is derived from living organisms and plays an important role in the C cycle (Paustian *et al.* 1997). Soil is a major reservoir of soil C with 3.3 times the size of the atmospheric pool of 760 petagram (Pg), and 4.5 times the size of biotic pool of 560 Pg (Lal 2004). Soils act as a reservoir of SOC and the level of storage within an ecosystem is mainly dependent on the soil type, climate, land use history and current management practices. The quantity of SOC stored in a particular soil is dependent on the quantity and quality of organic matter returned to the soil matrix, the soil's ability to retain SOC (a function of texture and cation exchange capacity), and abiotic influences of both temperature and precipitation (Grace *et al.* 2005).

SOC is essential for maintaining fertility, water retention, and plant production in terrestrial ecosystems with different land uses (Grace *et al.* 2006). Soil organic matter (SOM) maintains soil structure and productivity in agro-ecosystems (Lal 2010). Maintaining high levels of SOM is beneficial for all agriculture and crucial to improving soil quality. SOM has been widely used as an effective indicator of the functional response of soils to land use intensification (Dalal *et al.* 2003).

2.1.2 How is SOM related to SOC

Soil organic matter is the vast array of C compounds in soil and the SOC is the C component of the SOM. Therefore, the SOC is the percentage measure of C derived from living organisms and it is commonly represented as $SOM = SOC \times 1.72$, with 1.72 as the most commonly used conversion factor (Baldock and Skjemstad 1999). This is based on the assumption that SOM has 58% C content, on average. It is advantageous to report SOC rather than SOM for making consistent and reliable comparisons between studies. Recently, a conversion factor of 2.0 was proposed to be more accurate and representative based on the fact the most published literature averaged content of 50% C rather than 58% (Pribyl 2010).

2.2 Factors affecting SOC

2.2.1 Climate

The decomposition of SOM depends on its nature and abundance, and on climatic factors, in particular temperature and humidity, which influence the decomposition processes through their effects on microbial activity in the soil (Leirós *et al.* 1999). 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). Potter *et al.* (2007) conducted a multi-year study at six locations in central Mexico with a wide range of climatic conditions to determine the effect of varying rates of residue removal with no-till on SOC. They found that retaining 100% of the crop residues with no-till always increased or maintained the SOC content. SOC increased in cooler climates, but as mean annual temperature increased, more retained crop residues were needed to increase the SOC. In tropical conditions (mean annual temperature $> 20^{\circ}\text{C}$), 100% corn residue retention with no-till only maintained SOC levels but did not increase them. Mean annual temperature had a greater impact on SOC than did annual rainfall. At the higher temperatures, most of the residue would decompose if left on the soil surface without improving soil C content (Potter *et al.* 2007).

Soil C represents a significant pool of C within the biosphere (Lal 2004) and climatic shifts in temperature and precipitation have a major influence on the decomposition and amount of SOC stored within an ecosystem and that released into the atmosphere (Grace *et al.* 2006). The effect of temperature and precipitation on decomposition of plant materials is shown (Figure 2.1) using Century soil C model simulations, where both temperature and moisture effects on SOM decomposition increase to a certain level following sigmoid functions (Parton *et al.* 1987).

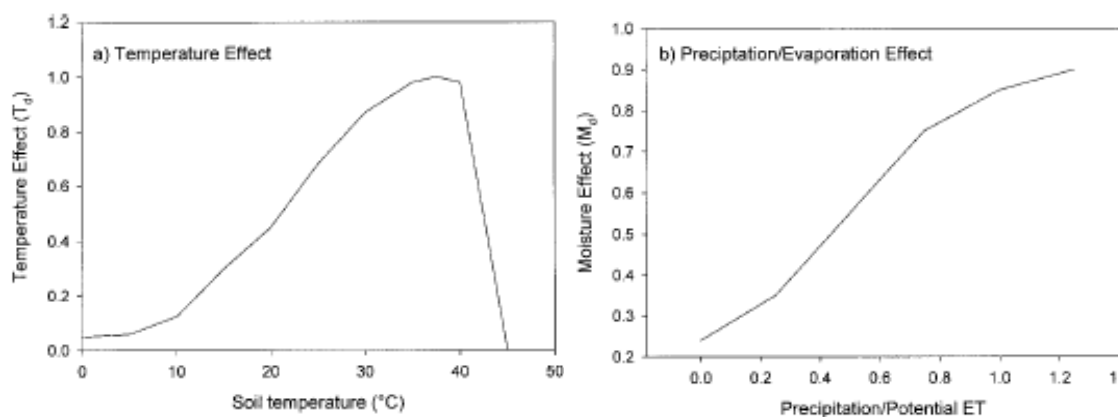


Figure 2.1. Effect of temperature and precipitation on decomposition (Parton *et al.* 1987).

Mean annual precipitation and mean annual temperature, have been used to explain spatial variation in global SOM levels (Post *et al.* 1982). SOC content increases with increasing precipitation; at a fixed precipitation level, it also increases with decreasing temperature (Post *et al.* 1982, McLauchlan 2006). 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 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).

In the presence of substrate, the decomposition rate of less decomposable materials appears to respond more to temperature than the decomposition rate of readily decomposable substrates (Conant *et al.* 2011). However, processes controlling substrate availability and the response of those processes to temperature as well as the intrinsic decomposition rate of the less decomposable compounds are also critically important (Kleber *et al.* 2011). Relevant field experiments are difficult to implement and the incubation studies have a limited capacity to shed additional light on the issue of temperature controls on changes in soil carbon stocks, except to the extent that they help us understand temperature controls on the components of decomposition of available SOM (Conant *et al.* 2011). Climate change could act as a driver for land use change, thus further altering terrestrial C fluxes. Due to the large size of terrestrial C pools, they have considerable potential to drive large positive climate feedbacks because increased CO₂ concentrations in the atmosphere will enhance climate change (Cox *et al.* 2000, Friedlingstein *et al.* 2006).

2.2.2 Soil type

Parent material partially determines the composition and content of clay minerals factors that are considered to be important in determining soil C longevity of agricultural soils (McLauchlan 2006). Clay minerals stabilise SOM, generally resulting in a positive relationship between SOC and clay content (Six *et al.* 1999, Chan *et al.* 2003). The influence of soil type of SOC is mainly on plant growth (Chan *et al.* 2003) and the protection of organic matter (particulate organic matter aggregates and organo-chemical complexes) (Hassink 1997, Six *et al.* 2000c) due to soil texture and cation exchange capacity (CEC). Soil type determines ability of soils to form soil aggregates, which is a result of the rearrangement of particles,

flocculation and cementation (Duiker *et al.* 2003) that stabilise SOC from being acted upon by microbes.

The rate and stability of aggregation generally increases with SOC or clay surface area and CEC. In soils with low SOC or clay concentration, aggregation would be dominated by cations, while the role of cations in aggregation may be minimal in soils with high SOC or clay concentration (Six *et al.* 2002a, Bronick and Lal 2005). Since texture of the soil has a significant influence on aggregation, increased clay concentration is associated with increased SOC stabilisation (Sollins *et al.* 1996, Hassink 1997, Francesca Cotrufo *et al.* in press).

The CEC is related to stability of soil aggregates (Dimoyiannis *et al.* 1998, McKenzie 1998) and the polycationic charges balances the repulsive forces between negatively charged clay or SOC complex (Bronick and Lal 2005). Soil texture is an important factor affecting the mineralisation due to its effects on pore size distribution that also affects the moisture release characteristics of soils (Thomsen *et al.* 1999). Soil pH influences SOC sequestration both through its influence on plant productivity and through the interactive effect on repulsive behaviour of negatively charged clay particles (Haynes and Naidu 1998).

2.2.3 Land use

The global decline in SOC as a result of deforestation, shifting cultivation and intensive arable cropping has made significant contributions to increased levels of atmospheric CO₂ (Post *et al.* 1990). Whether it is land use (e.g., woodland, pasture and crop land), cropping systems (conventional broad acre, intensive vegetable or organic horticulture) or the intensity of farming (number of crops grown in a year); key drivers of SOC dynamics are the quantity and quality (C:N ratio) of organic material entering soil (Wilhelm *et al.* 2004, Valzano *et al.* 2005, Yadvinder *et al.* 2005, Lemke *et al.* 2010) and the quantity of CO₂ emitted from the soil by microbial activity which is partly controlled by the level of soil disturbance (Angers *et al.* 1993, Six *et al.* 1999, von Lützow *et al.* 2006). The type of land-use directly affects both microclimate and the quantity and quality of C inputs, and the pathways of C cycling.

Erosion is controlled by land use and management and may decrease SOC stocks in agricultural systems compared with forests because it can be a major cause of SOC loss, particularly on poorly aggregated soils (Berhe *et al.* 2007). This is especially true for tropical regions with less fertile, highly weathered soils managed with few external inputs of nutrients

and C, which may be more susceptible to perturbations from land use changes with SOC turnover twice as high as in temperate regions (Six *et al.* 2002b). Land use effects across different soil types on soil C for parts NSW regions (semi-arid) of Australia were reported to be in the order: cultivated land < pasture < woodland (Wilson *et al.* 2008, Wilson *et al.* 2011). A similar trend is also reported for the three land uses in England, a cold temperate region (Saby *et al.* 2008). Woodland or forest produces the largest plant biomass than other land uses, and pasture does not undergo frequent cultivation unlike cropland, the above order is generally true for SOC storage capacity of the three broad land use categories.

The effect of land use change may be another way of looking at the changes due to land use. Meta-analyses have found that, if one of the land use changes decreased soil C, the reverse process increased soil C and vice versa (Guo and Gifford 2002, Don *et al.* 2011). For example, conversion of cropland to plantation increased SOC, but conversion of native forest to cropland decreased it because perturbations like tillage do not occur in plantation or native forest.

Within a particular land use system, specific agricultural management practices also affects SOC including tillage types, fertilisation, bare fallows, crop rotation and residue retention and so on (Johnson *et al.* 2007, Smith *et al.* 2008, Luo *et al.* 2010b, Sanderman *et al.* 2010). These are discussed in the following section.

2.3 Effect of agricultural management on SOC

2.3.1 Conservation agricultural practices

The recent review by Luo *et al.* (2010b) has synthesised published research that compares the conservation agriculture practices (CAP) with conventional practices in Australian agro-ecosystems and have shown the general increase in SOC sequestration by CAP compared to conventional methods. They have also shown that the introduction of perennial plants into a rotation had the greatest potential to increase soil C by 18% compared with other CAP. In a vegetable farming system, after three and a half years of adoption of conservation management including no-till and high inputs of compost with high content of organic C, the SOC in CAP was 75% higher than that in conventional management systems (Wells *et al.* 2000).

Despite adopting CAP, some studies have found no change or even a decrease in SOC over time (Heenan *et al.* 1995, Hulugalle *et al.* 2002, Hoyle and Murphy 2006, Baker *et al.* 2007) because the soil could have had a delayed response to CAP being implemented. Some studies with time series data suggest that the relative gain is often due to a reduction or cessation of soil carbon losses rather than an actual increase in stocks (Sanderman and Baldock 2010, Sanderman *et al.* 2010). This is because soil aggregation process that decrease SOC mineralisation could be slower than their destruction during tillage (Jastrow 1996, Six *et al.* 2000a) and thus SOC may not build up as quickly as they appear to be lost (Balesdent *et al.* 2000). Pankhurst *et al.* (2002) demonstrated this concept of hysteresis by applying tillage to previously tilled and no-till plots after a halt of three years; no-tilled plots showed large SOC losses whilst the tilled ones did not respond to the tillage.

2.3.2 Crop residue and its quality for SOC stabilisation

The addition of new residues in no-till management promotes organic matter stabilisation through the binding of primary soil particles and old microaggregates into new macroaggregates (Puget *et al.* 1995, Six *et al.* 1999). Fragmented crop residues, i.e., particulate organic matter (POM) can form the nuclei for new microaggregates that can be bound together by transient, labile organic matter to form new macroaggregates, or new microaggregates may form within the larger macroaggregates around POM (Golchin 1994, Six *et al.* 1998). Recently decomposed crop residues and SOM are central to the aggregate hierarchy model of Tisdall and Oades (1982). They proposed that transient forms of SOM could act as binding agents, causing microaggregates ($< 250 \mu\text{m}$) to form stable macroaggregates ($> 250 \mu\text{m}$).

Several studies have shown that incorporation of residue-derived C into aggregates increased with increasing aggregate size (Jastrow 1996, Six *et al.* 2000c, Puget and Drinkwater 2001). Consequently, macroaggregate formation could be enhanced by residue additions throughout the entire plough layer with tilled management. In contrast, under no-till management, residues are concentrated near the soil surface so that a smaller soil volume is exposed to fresh residues, which may limit new aggregate formation. Tillage has a strong influence on soil aggregation and SOM dynamics by increasing macroaggregate turnover and reducing microaggregate formation compared with no-till management (Six *et al.* 1999). The stabilisation of SOM may be enhanced in no-till management because macroaggregates that are formed are less susceptible to disruption from tillage-induced physical disturbances.

However, when residues are distributed to a 0.3-m depth, the negative impact of aggregate disruption through tillage appears to be counterbalanced, with similar efficiencies of C stabilisation between the no-till and tilled management practices, possibly due to slower decomposition of residues in the deeper soil profile (Baker *et al.* 2007, Olchin *et al.* 2008).

When crop residue is applied to soil, the composition of residue strongly affects the rate of crop residue decomposition and nutrient dynamics. As microorganisms have a low C:N ratio, residues with high C:N ratio (e.g. corn) are decomposed more slowly than residues with low C:N ratio (e.g. cabbage) and may lead to N immobilisation in the microbial biomass (Trinsoutrot *et al.* 2000a, Moritsuka *et al.* 2004). Moreover, the decomposition rate is positively correlated with the concentration of soluble sugars, proteins, and in the later stages of decomposition, with the concentration of cellulose (Gunnarsson *et al.* 2008), whereas high lignin concentration or high lignin:N ratio negatively affects the decomposition rate (Trinsoutrot *et al.* 2000b, Wang *et al.* 2004).

2.3.3 Crop residue management

There are several options for management of crop residues based on the requirements of the farmers. The options include removal from the field, incorporated into the soil, burned *in situ*, composted, or left on the soil surface as mulch for succeeding crops (Wilhelm *et al.* 2004, Yadvinder *et al.* 2005, Lemke *et al.* 2010). However, stubble retention, incorporation and burning are the main three stubble management practices in Australian conditions (Valzano *et al.* 2005). The off-farm uses of crop residues have increasingly being practised. Crop residues are removed from the field for feed/bedding for livestock, a substrate for composting, biogas generation or mushroom culture, or as a raw material for industry (Wilhelm *et al.* 2004, Yadvinder *et al.* 2005, Lemke *et al.* 2010). In the US, corn has considerable potential for fuel production because of the large amount of residue it produces although other high residue crops, such as rice and sugarcane, contribute to biofuel production as a solution to their residue disposal issues (Wilhelm *et al.* 2004, Blanco-Canqui and Lal 2007). Due to the high demand for crop residues for off-farm uses, the concern for maintaining SOC is a critical issue among researchers (Blanco-Canqui and Lal 2007, Lemke *et al.* 2010).

Crop residue burning converts biomass C into CO₂ and black C which is similar to charcoal. Burning of crop residue or stubble generally leads to a reduction of soil C (Luo *et al.* 2010b). The high temperatures generated by fire affects microbial activity in the surface soil, alters

soil structure and soil hydraulic properties (Kumar and Goh 1999, Valzano *et al.* 2005). The remaining black C is resistant to microbial decomposition and can persist in the soil for centuries (Harden *et al.* 2000). For this reason, black C has been proposed as a method to store C and offset the anthropogenic emission of CO₂ (Marris 2006, Lehmann 2007). Stubble retention has been shown to increase relative change in soil C over burning (Luo *et al.* 2010b). The synergistic effect of combining stubble retention and conservation tillage increased SOC content by 16% as compared with stubble burning and conventional tillage. This benefit is significantly higher than the separate application of these two practices, with 6% for stubble retention and only 3% for conservation tillage (Luo *et al.* 2010b). 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). Crop residue management systems that maintain organic materials *in situ* can benefit SOM (Hulugalle and Scott 2008, Liu *et al.* 2009, van Groenigen *et al.* 2011) and could, in the long term, offset the increasing concentration of atmospheric CO₂ by stabilising more carbon in soil (Mondini *et al.* 2007).

2.3.4 Crop residue and tillage

The effects of tillage and crop residue management can have opposing influences on SOC (Dong 2009, Liu *et al.* 2009, Dalal *et al.* 2011) and may be difficult to isolate. The type of tillage determines the rate of SOC breakdown whilst crop residue management determines the rate organic C input to a system (Liu *et al.* 2009, van Groenigen *et al.* 2011). For practical assessment, quantification of the effect of each of the two practices individually is desirable to enable evaluation of their separate contributions (Liu *et al.* 2009, van Groenigen *et al.* 2011).

Tillage breaks soil clods, redistributes and incorporates crop residue and soil amendments in soil profile, aerates the soil and recycles nutrients in the rooting zone (Dao 1998, Conant *et al.* 2007). Soil tillage management can affect factors controlling soil respiration, including substrate availability, soil temperature, water content, pH, oxidation-reduction potential, kind and number of microorganisms, and the soil ecology (Kladivko 2001). Tillage also exposes organic C in both the inter- and intra-aggregate zones, where C is vulnerable to rapid oxidation (Roscoe and Buurman 2003). This is because of the improved availability of O₂, water and the decomposition surfaces, thereby stimulating increased microbial activity (Beare *et al.* 1994, Jastrow 1996).

Whether to incorporate stubble into soil or not is an important farm management decision because terrestrial C sequestration has been suggested as a potential strategy for greenhouse gas mitigation (Valzano *et al.* 2005). The manner by which crop residues are introduced to the soil matrix differs dramatically between no-till and tilled management and thus aggregate turnover the two tillage treatment differs, as shown in Figure 2.2. In no-till management, crop residues are left on the soil surface after harvest, whereas residues are mechanically incorporated into the soil during tillage (Baker *et al.* 2007, Olchin *et al.* 2008). Studies tracking stable isotopes shifts in SOC fractions have shown that tillage increases the SOM decomposition rates (Paustian *et al.* 2000, Kisselle *et al.* 2001). To improve soil C sequestration in rotations, the input of residue and the CO₂ emission should be balanced by adopting appropriate tillage and residue management practices (Bàrberi 2006, Dong 2009).

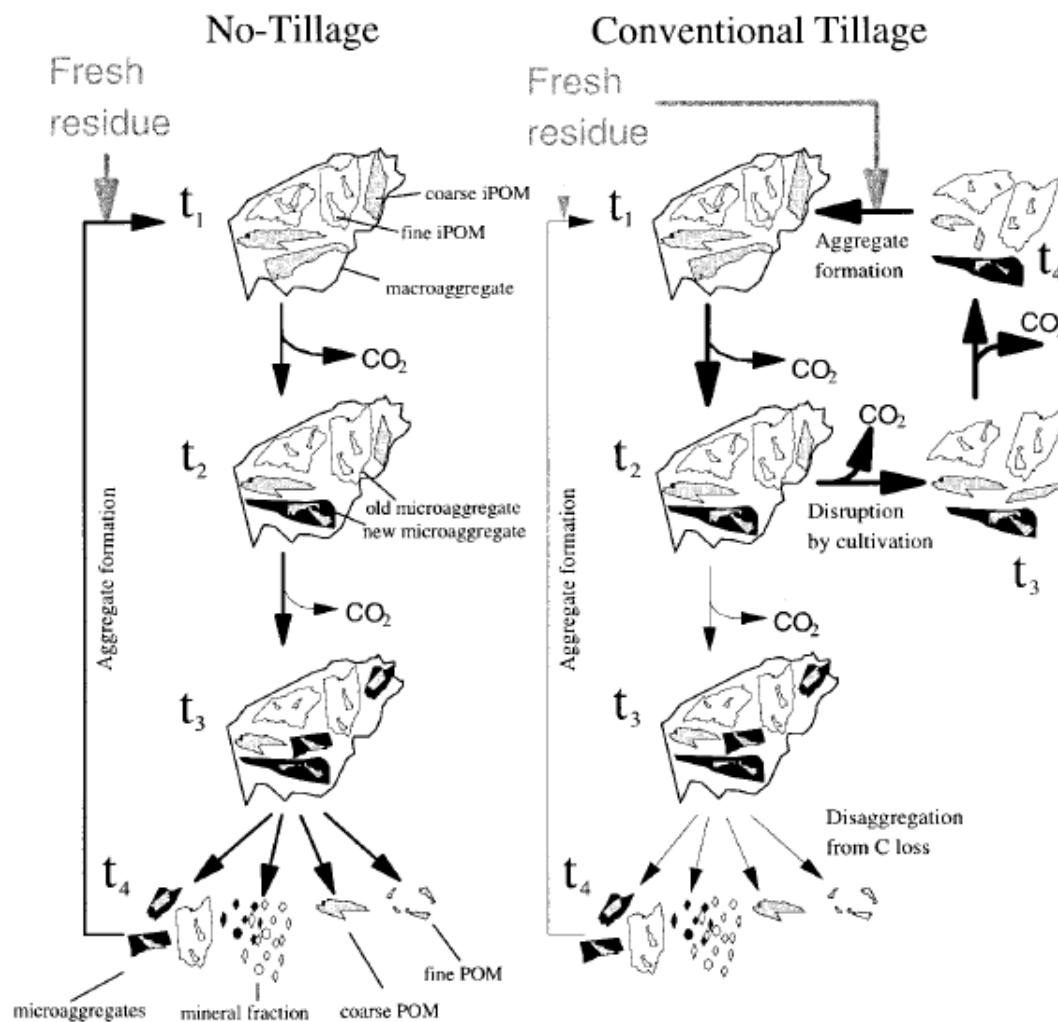


Figure 2.2. Conceptual model of aggregate turnover (Six *et al.* 1999).

Clapp *et al.* (2000) attempted to separate the roles of residue, tillage and N fertilization in SOM accrual by determining the source of C in the organic matter over a period of 13 years.

All three management factors affected SOC storage. Corn derived SOC was greatest under no-till without residue removal but lowest in no-till when stover was removed. Conventional and reduced tillage treatments were intermediate regardless of whether residues were harvested or returned. In one of the few studies that compared residue removal effects under moldboard ploughing, Reicosky *et al.* (2002) found that total C and N remained virtually unchanged over the 30-year study. This is in agreement with the study by Clapp *et al.* (2000), which found that when the soil was moldboard ploughed, residue with additional N fertilization did not increase SOC. Similarly, Dick *et al.* (1998) concluded that tillage and rotation had greater effects on C accrual than did residue removal.

Baker *et al.* (2007) argued that in no-tilled soils the SOC is concentrated near the surface, while in tilled soils it is distributed deeper in the profile; so that apparent SOC gains from no-till based on near-surface samples disappear when deeper samples are included. In another study where residues are distributed to a 0.3 m depth, the negative impact of aggregate disruption through tillage appears counterbalanced, with similar efficiencies of C stabilisation between the no-till and tilled management practices, possibly due to slower decomposition of residues deeper in the profile (Balesdent *et al.* 2000, Olchin *et al.* 2008).

2.3.5 Fertiliser management

Fertilisers and irrigation water are applied to soils in order to maintain or improve crop yields. In the long-term, increased crop yields and organic matter returns with regular fertiliser applications result in a higher SOM content and biological activity being attained compared to practices where no fertilisers are applied (Haynes and Naidu 1998). Since N is an important limiting soil nutrient that determines net primary productivity, its effect is of major significance to C sequestration in soil. In a recent comprehensive review of the effect of N management on C sequestration in North American cropland soils, Christopher and Lal (2007) concluded that, in most cases, N-fertiliser addition either had limited effect or, more likely, resulted in an increase in SOC. This was credited to the fact that SOC was linearly correlated to the amount of crop residues returned to the soil and crop residue production was directly related to N addition. 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 the soil (Alvarez 2005), confirming the important role of crop residue for C sequestration in soil. Similarly, Dalal *et al.* (2011) in a 40-year study found that crop residue retention increased SOC only when N fertiliser was applied, and fertilisation increased SOC

only when crop residue was retained, highlighting the synergy of fertilisation and residue retention. Although N fertiliser application increases crop yields, it may also accelerate mineralisation of SOM (Khan *et al.* 2007, Russell *et al.* 2009) or reduce aggregate stability (Fonte *et al.* 2009) potentially negating any incremental yield benefits associated with its use.

2.3.6 Organic farming

One of the alternatives to conventional farming systems is organic farming, which is claimed to prevent or to mitigate negative environmental impacts of intensive agriculture (Mäder *et al.* 2002, Leifeld *et al.* 2009, Mazzoncini *et al.* 2010). In organically managed farms, increased levels of soil organic matter (SOM), and hence increased reservoirs of nutrients are widely reported (Stockdale *et al.* 2001, Mäder *et al.* 2002). The regular use of manure is an important means in such cropping systems to maintain these high levels of SOM (Watson *et al.* 2002, Marinari *et al.* 2010a). However, SOM is a relatively stable parameter that reflects the influence of management over decades (Pulleman *et al.* 2000, Kirkby *et al.* 2011) rather than tracking the changes in biologically based soil fertility at a time scale of several years after changing conventional into organic farming (Wander *et al.* 1994). Biologically active or labile C fractions of SOM are likely controlled by management to a much greater extent than total SOM (Marriott and Wander 2006b).

Through the physical input of C from manures, compost or other organic fertilisers, SOC 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). Carbon sequestration involves net transfer of atmospheric C into land and addition of organic materials in soil under organic systems is the mere transfer of C from one location to another and is not C sequestration (Powlson *et al.* 2011). Moreover, crop yields in organic systems are generally lower than that of a conventional systems that use mineral fertilisers (Seufert *et al.* 2012) because the former is restricted by limited N and P supply (Berry *et al.* 2002).

2.3.7 Organic and conventional vegetable systems

While no-till farming is suitable for broadacre crops it is not commonly used in vegetable cropping systems. The reliance of the vegetable systems on tillage to perform basic management operations are proven to break soil structure and aggregates exposing the

physically protected soil organic matter for microbial attack, which stimulates the release of CO₂ to the atmosphere (Angers *et al.* 1993, Six *et al.* 1999, von Lützow *et al.* 2006). Despite requiring multiple tillage operations, the vegetable systems are characterised with little or no crop residue input (Jackson *et al.* 2004, Chan *et al.* 2007) to offset the loss of C induced by the tillage. Soil C in organic systems is generally reported to be higher than 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, the distinction between organic and conventional systems is still not clear even though the former relies heavily on organic materials for crop nutrition and thus, are claimed to store more SOC.

Organic vegetable systems rely on tillage for weed control, whereas conventional systems use herbicides to manage weeds (Bond and Grundy 2001, Chirinda *et al.* 2010). In addition, organic systems use organic sources, such as crop residue and compost, for fertilisation but conventional systems 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. The slower nutrient releasing properties of organic fertilisers may help in retaining more nutrients in soil than the soluble mineral fertilisers (Berry *et al.* 2002, Marinari *et al.* 2010a). The former may reduce the amount of nutrients lost to the environment via leaching (Poudel *et al.* 2002, van Diepeningen *et al.* 2006) or in gaseous forms (Bouwman *et al.* 2002). Soil nutrient reserves and underlying nutrient cycling processes in organically cropped soils are similar to that in conventionally managed soils, however the former holds nutrients in less-available forms (Berry *et al.* 2002, Stockdale *et al.* 2002), which is of a greater significance.

2.4 Pools of C and C stabilisation mechanisms

Crop residue or organic fertiliser undergoes a series of processes in soil leading to different pools such as a labile or active pool, intermediate or slow and stable or inert or recalcitrant pools (Smith *et al.* 1997). These are conceptual pools with characteristic turnover rates ranging from less than one year to thousands of years. The pools exist in a continuum between labile and stable pools, as shown in Figure 2.3, rather than fixed pools (Davidson and Janssens 2006). These conceptual SOM pools are defined by their different turnover times and their pool sizes (Smith *et al.* 1997, von Lützow *et al.* 2007). The SOC functional pools

concept has been summarised using the Century and Roth-C models that capture the main characteristics of the three pools (Davidson and Janssens 2006, Kleber and Johnson 2010).

The labile C fractions are increasingly used in agro ecosystems research because they respond more sensitively to changes in land management (Cambardella and Elliott 1992, Chan 1997). Labile fractions of C are closely linked to soil microbial biomass and organic matter turnover and can serve as indicators of the key chemical and physical properties of soils such as infiltration (Bell *et al.* 1999) and the availability of labile nutrients such as N, P and S (O'Donnell *et al.* 2001).

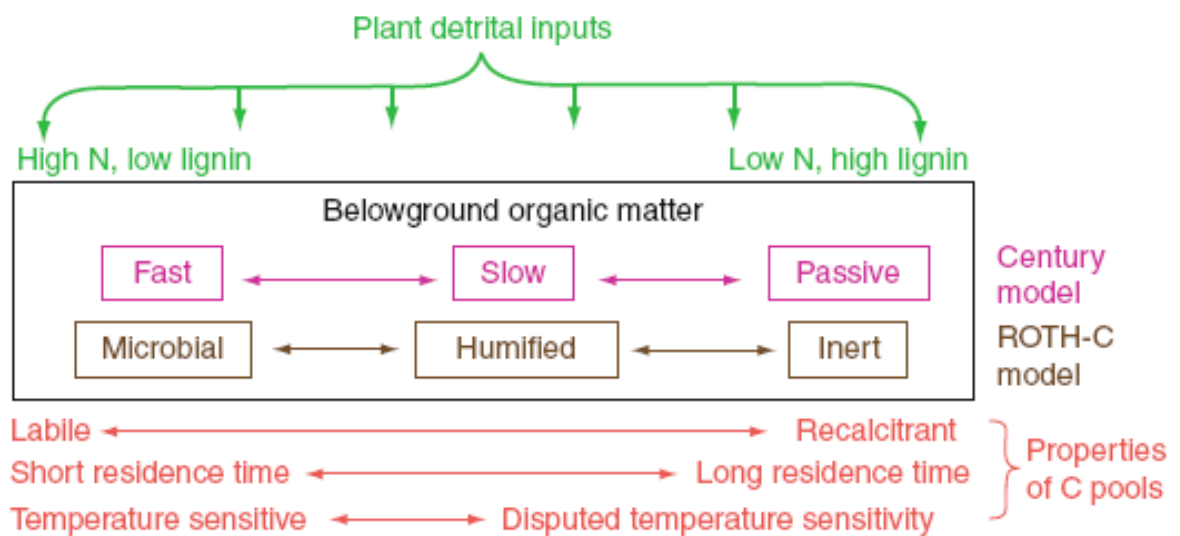


Figure 2.3. Diagram of inputs to and some characteristics of SOC functional pools (Davidson and Janssens 2006).

2.4.1 Labile and particulate organic C

Labile pools, often referred to as unprotected C, are characterised by a rapid turnover, mainly consist of young SOM, and are sensitive to land management and environmental conditions (Parton *et al.* 1987). These labile C has a short residence time and is subject to fast mineralisation whereas the stable C has long residence time and is recalcitrant in nature (Davidson and Janssens 2006, Kleber and Johnson 2010). Owing to these features, labile SOM pools play an important role in short-term C and N cycling in terrestrial ecosystems (Schlesinger 1990, O'Donnell *et al.* 2001). The most commonly isolated labile C pools are the light fraction (LF) and particulate organic matter (POM). The LF consists mostly of mineral-free, partly decomposed plant debris (Spycher *et al.* 1983) and appears in soils as free POM (Golchin 1994, Six *et al.* 1998). When free POM is further decomposed, it can be

incorporated into aggregates, where its decomposition is restricted (Golchin 1994, Puget *et al.* 1995). In this case, POM becomes part of a less labile pool, but is easily decomposable when it is released again; hence the degree of protection of labile C is dependent on aggregate turnover. Stabilisation of occluded organic matter is greatest when aggregate stability is high and aggregate turnover is slow (Six *et al.* 1998).

2.4.2 Soil C stabilisation through aggregation

For soils to act as a C sink, organic C needs to be stabilised in stable C pools (Paustian *et al.* 1997). Of the stable C pools, SOC protected within aggregates is sensitive to land management practices such as manure application, tillage, or crop rotation (Six *et al.* 1999). Therefore, the amount of C stabilised in protected SOC pools is critical for the determination of the extent to which soils can operate as a C sink under specific management conditions. Due to different protection mechanisms, the degree and the duration of stabilisation of SOC within macroaggregates and microaggregates differ (Tisdall and Oades 1982). Macroaggregates contain soil C that (a) functions as transient binding agents holding microaggregates together and (b) are occluded within microaggregates, which results in greater absolute C contents of macroaggregates than microaggregates (Tisdall and Oades 1982, Elliott 1986).

The aggregation model of C stabilisation is based on the size of soil aggregates where macroaggregates provide minimal physical protection (Elliott 1986, Beare *et al.* 1994) and microaggregates, including those within macroaggregates, provide more physical protection against microbial decomposition (Six *et al.* 1999, Balesdent *et al.* 2000, Blanco-Canqui and Lal 2004). Stabilisation is determined by the silt plus clay content ($< 53 \mu\text{m}$) 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, water and oxygen (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). Microaggregates have a smaller C storage potential, but as they sequester C in the long term (Skjemstad *et al.* 1990, Six *et al.* 2000a), the degree of stabilisation is greater. Increased organic matter input to soil through management practices such as animal or green manure application and straw incorporation

increases the SOM content (Mikha and Rice 2004) and enhances soil aggregation (Sommerfeldt and Chang 1985).

2.4.3 Physicochemical stabilisation

The physicochemical stabilisation of SOC is due to the sorption of SOC compounds on silt plus clay surfaces ($< 53 \mu\text{m}$) or mineral colloids (Hassink 1997, Christensen 2001, von Lützow *et al.* 2006). 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 longer a 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 why there is reduction of microbial decomposition of the SOC particles bound on mineral surfaces (von Lützow *et al.* 2006). Isotopic studies have shown that early-stage leaf and root litter decomposition products contribute a relatively large amount of C to mineral soil (Bird *et al.* 2008, Rubino *et al.* 2010) and that this contribution is mainly from microbial compounds produced during the degradation process of litter (Mambelli *et al.* 2011). However, recalcitrant plant components (e.g., lignin and phenols) do not preferably accumulate in SOM (Marschner *et al.* 2008). Labile plant components, not the recalcitrant ones, are dominant sources of microbial breakdown products because they are utilised more efficiently by microbes, and thus become the primary precursors of stable SOM by promoting aggregation and through strong physicochemical bonding to the soil matrix (Francesca Cotrufo *et al.* in press).

2.5 Fractionation and laboratory analysis of SOC

2.5.1 Fractionation for measurement of SOC pools

Stability of SOM can be defined in terms of how easily C and N in the SOM can be decomposed. The identification, isolation and characterisation of SOM fractions have received a great deal of scientific interest because of their implications in the permanence of SOC during sequestration (Plante *et al.* 2011). The estimates of different pools are used in mechanistic models (e.g. Roth-C and Century) that predict changes in SOM storage (Parton *et al.* 1987, Coleman *et al.* 1997). A large number of SOM fractionation procedures have been developed that seek to distinguish between SOM that is more easily decomposed (low stability) and less easily decomposed (high stability) by the soil microbes. The procedures

have been recently reviewed and include physical fractionation by size or density, and various chemical fractionation methods that separate SOM by solubility, hydrolysability, or resistance to oxidation (von Lützow *et al.* 2007).

Physical fractionation procedures by size is based on the idea that the association of soil particles and their spatial arrangement play a key role in SOM dynamics as bioaccessibility is a prerequisite for decomposition (Christensen 2001). Physical fractionation involves the application of various degrees of disaggregating treatments by dry and wet sieving (Christensen 1992, Six *et al.* 1999, Six *et al.* 2000a), dispersion (Cambardella and Elliott 1992), and density separation and sedimentation (Christensen 1992, Golchin 1994). The extraction method developed by Cambardella and Elliott (1992) is commonly used to isolate particulate ($> 53 \mu\text{m}$) and mineral-associated organic C fractions ($< 53 \mu\text{m}$) after dispersion of soil samples in potassium hexa-meta phosphate solution (5g/L) and tumbled overnight. Based on the extraction component of Cambardella and Elliott (1992), an automated wet sieving technique was developed in Australia using $50 \mu\text{m}$ sieve so that $> 50 \mu\text{m}$ fraction consists of POM plus sand and $< 50 \mu\text{m}$ fraction of mineral-associated organic matter (Sanderman *et al.* 2011).

The general wet sieving process uses sieves of $250 \mu\text{m}$ and $53 \mu\text{m}$ to isolate fractions into three aggregate groups. The $> 250 \mu\text{m}$ is macroaggregate, $250\text{--}53 \mu\text{m}$ is microaggragate and $< 53 \mu\text{m}$ is silt + clay size fraction (Six *et al.* 1999, Six *et al.* 2000a). Density fractionation is applied to isolate SOM that is not firmly associated with soil minerals from organo–mineral complexes (Christensen 1992, Golchin 1994). Associations of SOM to mineral surfaces are most often characterised by a density $> 1.6\text{--}2 \text{ g/cm}^3$. The fraction of SOM that floats in the $> 1.6\text{--}2 \text{ g/cm}^3$ medium is the light fraction and that settles down is the heavy fraction. Lighter fraction or POM with a density of $> 1.6\text{--}2 \text{ g/cm}^3$ consist mostly of pieces of plant residues and heavier fraction consists of mineral-associated organic C (Christensen 1992, Golchin 1994). POM also has been separated by a combination of size and density fractionation (Balesdent *et al.* 1998, Six *et al.* 1998, Six *et al.* 2000b).

Of the five SOC pools in the Roth-C model, the inert pool (Coleman *et al.* 1997) is considered to be totally unaffected by microbial attack and thus to undergo no decomposition with time (Falloon *et al.* 2000). Several chemical fractionation methods have been used for the isolation of stable SOC; hydrolysis using trifluoroacetic acid (TFA) and hydrochloric acid (HCl) (Poirier *et al.* 2003, Quénéa *et al.* 2006), oxidative treatments using several oxidants like

hydrogen peroxide (H_2O_2) (Plante *et al.* 2004), disodium peroxodisulphate ($\text{Na}_2\text{S}_2\text{O}_8$) (Eusterhues *et al.* 2003), or sodium hypochlorite (NaOCl) (Kleber *et al.* 2005). Hydrolysis removes compounds that are supposed to be potentially biodegradable (Poirier *et al.* 2003, Quénéa *et al.* 2006), whereas it has been suggested that the treatments using oxidizing reagents to mimic biodegradation to the extent that treatments preferentially remove less protected SOC (Plante *et al.* 2004, Kleber *et al.* 2005). Helfrich *et al.* (2007) compared five chemical fractionation methods and found that all chemical treatments caused a preferential removal of young, maize-derived SOC, with $\text{Na}_2\text{S}_2\text{O}_8$ and H_2O_2 being most efficient. However, none of the methods were reported to be generally suited for the determination of the inert organic matter pool of the Roth-C model (Helfrich *et al.* 2007).

2.5.2 Laboratory determination of SOC

The most commonly used methods for determination of SOC are wet oxidation by Walkley-Black method (Kalembasa and Jenkinson 1973) and dry combustion by LECO CN Analyzer (Nelson and Sommers 1996). The latter method estimates SOC more accurately. Due to incomplete oxidation of SOC in a dichromate-sulphuric acid mixture, the Walkley-Black method underestimates SOC concentration when no heating is applied. To overcome the problem of incomplete C recovery, which leads to the underestimation of C concentrations by Walkley-Black method, the analytical results of this technique are adjusted by 1.32 as a correction factor assuming the recovery rate of 76% (Gillman *et al.* 1986). However, modified dichromate oxidation techniques that involve extensive heating do not require a correction factor because most of the organic C in the soil is oxidized to CO_2 (Kalembasa and Jenkinson 1973). Some authors reported that the recovery of 76% is generally too large (Diaz-Zorita 1999, Brye and Slaton 2003) and that it may vary according to land use, soil texture and sampling depth (Diaz-Zorita 1999, Brye and Slaton 2003, Lettens *et al.* 2007).

The development and emergence of reflectance spectroscopy techniques, near infrared (NIR) and mid-infrared (MIR) are also used to determine SOC in the laboratory. Using chemometric statistical methods, both NIR and MIR spectroscopy techniques have been used in the past two decades to determine soil properties, including soil organic C and total N (Janik *et al.* 1998, Zimmermann *et al.* 2007, Yang *et al.* 2012). Compared with wet and dry combustion methods, the NIR and MIR spectroscopy techniques are rapid, robust, inexpensive and non-destructive, and they do not require any reagents for analysis (Janik *et al.* 2007, Vasques *et al.* 2008). These emerging techniques are, therefore, likely to replace the tedious job of wet and

dry combustions in future, and are highly attractive for studies where a large number of analyses are required (Yang *et al.* 2012).

These techniques are also used for *in situ* measurement of SOC in the field by sampling, or on-the-go with sensors mounted on a tractor (Cécillon *et al.* 2009, Bellon-Maurel and McBratney 2011). Remote sensing is another tool for *in situ* measurement of soil properties in the field (Ben-Dor *et al.* 2002).

2.6 Research gaps and conclusion

Concerns about declining SOC and increased greenhouse gas emissions due to farming practices such as intensive tillage and bare fallows have encouraged the 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 suitable 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 cultivations break soil structure and aggregates exposing the physically protected soil organic matter for microbial attack, which stimulates the release of CO₂ to the atmosphere (Angers *et al.* 1993, Six *et al.* 1999, von Lützow *et al.* 2006). Despite requiring multiple tillage operations, the vegetable systems are characterised with little or no crop residue input (Jackson *et al.* 2004, Chan *et al.* 2007). In this light, sweet corn, a relatively high value vegetable crop, was proposed as a rotation crop for a vegetable system so that there would be abundance of residue available as input to soils. Furthermore, organic vegetable systems rely on tillage for weed control (Bond and Grundy 2001, Chirinda *et al.* 2010). While there are many studies looking at the effect of residue retention on the soil surface on SOC, studies looking at the effect of residue incorporation on soil C are rare. There are research gaps particularly related to residue management in organic and conventional SMS prompting research questions such as:

- A. would organic SMS improve SOC in comparison conventional SMS in a vegetable system?
- B. would residue incorporation in soil in the two SMS maintain or increase SOC in a vegetable system that uses multiple tillage operations?
- C. would residue incorporation in soil in the two SMS increase soil C fractions, particularly the stable fraction? and
- D. would residue incorporation in soil offset the loss of CO₂-C caused by soil disturbance?

Hence, the effect of corn residue incorporation on soil C and its fractions, and CO₂-C emission in the two SMS were proposed to be examined as an alternative to removal of residue.