NSW Agriculture

Soil Carbon Sequestration Utilising Recycled Organics

A review of the scientific literature

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The Organic Waste Recycling Unit, NSW Agriculture

T.S. Gibson, K.Y. Chan, G. Sharma and R. Shearman

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Executive Summary

This study was commissioned by Resource NSW to review the scientific literature and assess the potential for:

- recycled organics products to increase the sequestration of organic carbon in NSW soils, and
- sequestered soil carbon (from recycled organics products) to qualify for inclusion in Australia's National Carbon Accounting System and be traded as carbon credits.

Soil Organic Carbon and Carbon Sequestration in NSW Soils

Soil organic carbon (SOC) is the carbon component of soil organic matter directly derived from plants and animals. It exists in a continuum of organic compounds in different stages of decomposition that represent organic pools of differing lability or turnover times. The ultimate product of the decomposition process is humus, an amorphous array of compounds highly resistant to further decomposition. Soil organic carbon also constitutes a significant proportion of the terrestrial carbon store and carbon fluxes in the global carbon balance and therefore has the potential by the decomposition of its labile fractions, to influence levels of atmospheric carbon dioxide. Soil organic carbon has pivotal roles in a number of physical, chemical and biological quality parameters that contribute to soil productivity and sustainability.

Natural equilibrium levels of SOC are determined primarily by the influences of climate (temperature and rainfall) and soil texture. Changes in SOC levels reflect the net balance between gains and losses of organic material. Conventional soil cultivation practices promote the mineralisation (oxidation) and loss as carbon dioxide (CO_2) of the more labile SOC fractions. Soil management practices such as conservation farming are designed to increase carbon inputs and minimise the carbon losses that are characteristic of traditional cultivation practices.

Despite increased adoption of conservation farming practices, cropping soils in NSW within a 250 km radius of the Sydney Basin are low in organic carbon compared to their natural equilibrium levels. Although these soils are typically light in texture and their capacity to sequester carbon is limited, they offer opportunities to sequester SOC by the development and application of improved management systems. Estimates of the carbon sequestration potential of NSW soils from experimental data by paired sites comparisons and modelling with the CENTURY model ranged from 6 to 40 t/ha, depending on soil texture and climate. Even with the most conservative estimate of the potential for carbon sequestration per ha in light textured soils, the cereal cropping soils alone in the Central Western district of NSW offer a potential sink for over 5 million tonnes (over 5

Tg) of carbon from recycled organics (RO). This represents a modest contribution to carbon sequestration in the overall accounting process (SOC mineralisation from agriculture in Australia contributes 4 Tg carbon to the atmosphere every year). However, it offers a potential market for an estimated 137.5 million tonnes of RO product, which far exceeds the supply capacity of the RO industry in the Sydney Basin.

Composted RO products are an unrealised source of organic carbon for agricultural soils. These products are accumulating in the Sydney Basin and there are clear synergies between the available source of organic carbon in RO products and the low organic carbon status of NSW soils. The use of composted RO products as a part of a systems approach to improved soil management would provide an external source of stable organic carbon and has the potential to reverse some of the carbon losses in NSW cropping soils.

The Kyoto Protocol and Opportunities for Carbon Credit Trading in Sequestered Soil Organic Carbon

In recognition of the potential effects of unregulated greenhouse gas emissions on global climate the United Nations in 1992 adopted a Framework Convention of Climate Change to develop mechanisms to stabilise atmospheric greenhouse gases. In a subsequent agreement in 1997, the Kyoto Protocol, signatory nations agreed to account for their net carbon emissions to the atmosphere and to implement programs to reduce these emissions to target levels by the accounting period of 2008 to 2012, relative to the base year of 1990. The Kyoto Mechanisms of the Protocol include International Emissions Trading in which carbon is considered to be a tradeable commodity in an international market.

Agreements under the Kyoto Protocol initially focussed on emission reduction and carbon sequestration (the *additional* carbon stored during the accounting period) by forestry industries. In recent agreements under the Protocol, carbon sequestered in soil now qualifies for inclusion in the carbon accounting process (Article 3.4). However, the Australian Greenhouse Office is yet to determine if soil carbon will be considered for the National Carbon Accounting System. Inclusion of soil carbon sequestration for accounting purposes requires demonstration of transparency, consistency, comparability, completeness, accuracy and verifiability. In Australia it faces a number of challenges:

- Existing data on soil carbon stocks are not complete and in some cases not suitable for accounting purposes. The available data need to be collated and assessed on their suitability so as to identify the knowledge gaps. Additional sampling and analyses will be needed. Developments in analytical methods and simulation modelling processes are also necessary to verify changes in soil carbon stocks during the accounting period, as is agreement on standardised methods and which baseline soil carbon measurements are adopted. Several projects commissioned by the Australian Greenhouse Office have made some progress on these issues. However, much of the soil carbon data now being generated is limited to recently cleared areas. Existing soil carbon models such as the CENTURY model do not include inputs of stabilised organic carbon as composted products.

- Increases in levels of soil carbon through the use of RO on agricultural land is a complex and long term process, with only a fraction of the organic carbon applied as RO remaining as sequestered soil carbon. Little data are available from studies under Australian conditions on the effectiveness of RO to sequester soil carbon. Development of improved land management systems that combine the principles of conservation farming with strategic RO use is crucial to ensure that organic carbon inputs are conserved as much as possible within the constraints of the system. A better understanding of soil carbon dynamics would enhance the conservation process.

- An accounting or modelling system for soil carbon sequestration from recycled organics must involve a total carbon account to reflect all costs and benefits attributable to any claimed increase in soil carbon. This can be expressed in the equation:

Soil Carbon Sequestered	=	Direct Sequestration	+	Indirect Sequestration	-	Direct Carbon Losses	+	Avoided carbon Losses

Although direct carbon losses (carbon used in fuel consumption and fertiliser manufacture) and avoided carbon losses (the carbon savings or reduced carbon losses from the fertiliser value of RO) can be calculated, adequate data to determine direct sequestration (carbon derived directly from RO) and indirect sequestration (carbon derived from increased plant biomass) are not available in Australia.

- Some progress has been achieved in Australia on a carbon trading system based on forestry and a market in carbon has emerged. This and other international markets place various values on carbon credits, all of which are below a theoretical value of US$95 per tonne of carbon, based on the external costs of each tonne of carbon emitted to the atmosphere. In Australia, with decisions pending on the conclusion of soil carbon sequestration in the national accounting system, at present it is difficult to estimate the financial benefit to farmers if a trading system were established.

- The review recommends three actions:
  1. Studies to identify gaps in existing soil baseline data for SOC in targeted NSW soils based on soil texture, climatic zones and management practices.
  2. Research in targeted areas to identify key product specifications that would promote the potential to sequester carbon in soils, develop and validate effective soil carbon management strategies and to generate data necessary to develop modified soil carbon models that include RO carbon inputs.
  3. Clarification from the Australian Greenhouse Office on its position on soil carbon sequestration and the carbon accounting process in Australia

Introduction

This chapter sets the foundation for the literature review, establishing background information, the Kyoto Protocol and its relevance to soil carbon and the scope of the literature review.

1.1 Background

Soil organic carbon (SOC) is the carbon component of soil organic matter directly derived from plants and animals (Charman and Roper, 1991) and plays a central role in soil quality and the sustainability of soil fertility (Chan, 2001). However, traditional agricultural practices such as land clearing and cultivation of soil have led to land degradation, mineralisation of SOC and the subsequent loss of SOC as carbon dioxide (CO_2) emitted to the atmosphere (Lal *et al*, 1998; Hao *et al*., 2001). Globally, agricultural activities release 800 Tg C/yr (1 Tg = 10^{12}g) through the mineralisation of SOC (Schlesinger, 1990) and the Australian contribution is estimated to be 4 Tg C/yr (Swift, 2001). In Australia, approximately 75% of soils now contain less than 1% organic carbon in their surface horizons (Spain *et al*., 1983). Many of these soils are important for agricultural production.

Adoption of sustainable soil management practices such as conservation farming (involving minimum tillage, crop/pasture rotations, stubble retention and green manures, soil amendments with straw and animal manures) has had some success in slowing this trend of land degradation and decline of SOC (Lal, 1997; Chan and Pratley, 1998). These practices represent opportunities to accumulate SOC through the processes of carbon sequestration (Rosenzweig and Hillel, 2000; Smith *et al*., 2000a; Pretty and Ball, 2001).

Composted products derived from recycled organics (RO) present additional opportunities to increase SOC in many agricultural systems. Recycled organics are compostable organic materials, including garden organics, food organics, residual wood and timber, biosolids and agricultural residuals (ROU, 2001) and are high in organic carbon. With current NSW Government policies to reduce the amount of material disposed of to landfill, RO are now accumulating in the Sydney Basin in unprecedented quantities. Compostable organics entering the waste stream are estimated at 1.3 million tonnes per year, of which 20.6% is processed into RO products (ROU, 2002), primarily used in landscaping. Projected increases of garden organics entering the waste steam should be reduced by current and future governments' waste avoidance programs. However, clear synergies exist between the availability of organic carbon in RO soil-amendment products accumulating in the Sydney Basin and the need to sequester additional organic carbon in agricultural soils in NSW.

A major existing barrier to the widespread use of RO products in the agricultural sector is the prohibitive cost of material, transport and application. In NSW the RO sector is actively developing strategies to access agricultural markets (Love and Rochfort, 1999; Nolan ITU, 1999, Fahy and Richard, 2000; Bishop et al., 2001). Research has been primarily funded by Resource NSW (formerly NSW Waste Boards) and a NSW Agency/industry partnership of Sydney Water, NSW Agriculture, Waste Service NSW and Australian Native Landscapes. One potential option to make RO product use in agriculture more economically attractive is to use the capability of soil to sequester carbon (act as a net carbon sink) as a tradeable commodity in the carbon credit system established in 1997 under the Kyoto Protocol.

The Kyoto Protocol is an international treaty under which developed countries agreed to limit net 'greenhouse gas' (GHG) emissions to a specified percentage of 1990 levels. It grew from international recognition that human activity has increased emissions of gases that trap heat in the atmosphere and contribute to global warming. The primary sources for GHGs include the burning of fossil fuels, cement manufacture and changes in SOC sequestration caused by conversion from natural to agricultural ecosystems (Lal and Bruce, 1999). Greenhouse gases include water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), oxides of nitrogen (NO_x), tropospheric ozone (O_3), carbon monoxide (CO) and chlorofluorocarbon (CFC) (Lal *et al*., 1995). Carbon dioxide is the major GHG and estimates in Australia are that >95% of the GHG emission reductions from improved land management practices in 2000 are attributable to reductions in CO_2 emissions (Hassall and Associates, 2001). The relative impacts of the various GHGs on a per molecule basis are described as CO_2 equivalents, with CO_2 having an index of 1, and 25, 200 and 10,000 respectively for CH_4, N_2O and CFC (Johnson, 1995). To assist signatory countries to meet their GHG emission targets the Kyoto Protocol also included agreement on the use of a carbon emission trading system, which identified carbon sinks to offset carbon emissions. Atmospheric CO_2 is estimated to have increased from 280 ppm by volume in 1750 to 367 ppm in 1988 and a doubling of the pre-industrial concentration of CO_2 will increase average global temperatures by an estimated 1.4-4.5^{0}C (Edmonds, 1999). The Kyoto Protocol is more fully discussed in Section 5.

Global estimates are that the agricultural sector annually contributes 20% of the total GHG emissions (Lal and Bruce, 1999). Livestock industries are the single largest contributor to Australian agricultural GHG emissions, primarily as CH_4 (Hegarty, 2001). Other emission sources in agriculture include the direct use of fossil fuels in farm operations, the use of energy to manufacture farming inputs such as fertilisers and pesticides, and SOC mineralisation by the cultivation of soils (Pretty and Ball, 2001). Soil cultivation is estimated to contribute to the loss of 4Tg of soil carbon per annum, representing 50% of the CO_2 emissions in the Forest and Grassland

Conversion component of the Australian GHG inventory (Swift, 2001). The potential capacity for agricultural soils in NSW to sequester carbon might represent a tradeable carbon credit to offset GHG emissions under the Protocol. Although omitted from the original Kyoto agreement, cropping land and grazing land management are now included as eligible activities for carbon credits after clarification at a 2001 meeting in Bonn.

Composted RO products are also promoted as a means to increase the water holding capacity of soils and to remediate salt-affected soils. Salinity and water trading systems aim to decrease groundwater recharge or conserve scarce water resources. Does RO use in agriculture have a role in these schemes?

1.2 Scope of literature review

This review commissioned by Resource NSW has several objectives. It will:

- identify the potential of NSW agricultural soils to sequester carbon
- identify the benefits of RO products for soil fertility and productivity
- examine the potential for RO products to contribute to carbon sequestration.
- assess the potential for RO use on agricultural land to gain economic benefits from carbon credits under the Kyoto Protocol, and
- provide a brief overview of the potential for RO use on agricultural land to gain salinity and water credits

The review complements a recent investigation to identify GHG emissions from processing garden organics through commercial composting facilities (ROU, 2001). The web site of the Australian Greenhouse Office (www.greenhouse.gov.au) also provides extensive background information on the Kyoto Protocol and carbon accounting.

Landuse systems, soils and recycled organics

This chapter summarises the main landuse for cropping in NSW, identifies and characterises the principal soil types in NSW and provides information on the nature of recycled organics.

2.1 Land use systems in NSW

This review will consider the area of NSW within a 200-250 km radius of Sydney, which at present is the limit for transport and application of RO to agricultural land, as the target area for RO product application. Only 3.5 to 5.7 million ha (4.4 to 7.1%) of the total 80 million hectares available to agriculture in NSW agricultural land is estimated as being suitable for cultivation and an estimate of 500,000 ha is suitable continuous cropping (NSW EPA, 2000). Estimates of areas for the main cropping industries in NSW are given in Table 2.1, which focuses on the land area ‘available’ for RO application.

Table 2.1 Agricultural Cropping Land Use Areas in NSW (adapted from ABS, 1998)

	Landuse Area (ha)					
Statistical Division	Fodder Cereals*	Grain Cereals	Vegetables	Orchards**	Viticulture	Total
NSW	146,502	4,676,449	26,599	74,981	19,989	4,944,520
Sydney	750	638	2,079	5,266	30	8,763
Hunter	4,175	45,531	785	854	3,719	55,064
Illawarra	761	725	431	342	14	2,273
Central West	32,300	864,200	3,054	6,479	1,540	907,573

*hay, siliage or grazed
**excluding viticulture

Although this information is now several years old (revised ABS data will be released in 2002), Table 2.1 shows that the cropping areas in the Central West area provide by far the most land area potentially available for RO application. However substantial cereal cropping areas in the Hunter Valley, vegetable cropping and orchards in the Sydney Basin and viticultural areas in the Hunter Valley and Central West also offer opportunities. Viticulture is of particular interest because it has been identified in market studies as a significant potential market for RO use (Love and Rochefort, 1999). In summary, substantial areas of cropland within the defined boundary of 200-250 km of Sydney (the target area for RO use in agriculture) are potentially available for the application of RO. Other factors, particularly economic and the effectiveness of extension programs, will determine how much of this potential is realisable.

Table 2.1 emphasises cropping systems rather than pasture systems. This review is about RO and the potential for carbon sequestration in soils. Because of their cultivation-based management systems (see Section 4 for a discussion on conservation farming practices) cropping soils are inherently lower in organic matter and offer the best opportunity to sequester carbon. By contrast, well-managed pasture soils tend to retain higher soil organic matter because of annual inputs of organic residues from pasture and the absence of cultivation (Tisdall and Oades, 1982). Therefore, pasture soils offer less potential for additional carbon sequestration through RO addition.

2.2 Soil types in NSW

Different soil types differ in their capacity to sequester organic carbon supplied as RO. This capacity relies on the soils' inherent potential (based on texture, mineralogy, etc) to retain organic carbon (SOC equilibrium levels). Mechanisms in SOC sequestration will be discussed in Section 4. While the area of agricultural soils within the target area for RO use in agriculture is large (Table 2.1), the characteristics of these soils must also be considered for the estimation of SOC sequestration potential.

Where possible, this review will consider soil types in the context of the Australian Soil classification (Isbell, 1996). This soil classification lists 13 soil types, with the most common present in NSW listed below:

- Sodosols
- Kandosols
- Vertosols
- Calcarosols
- Chromosols
- Dermosols
- Tenosols
- Kurosols

The location of these soil types, their approximate equivalent classification in other soil classification systems such as Great Soil Groups (Stace *et al*., 1968) and US Soil Taxonomy (Soil Survey Staff, 1994), their soil properties, particularly their limitations, and land use within NSW are given in Table A1 (Appendix). The main soil types within a 200-250 km radius of Sydney and their properties are shown in Figure 2.1 and Table 2.2. The dominant soil types are in bold in Table 2.2.

Figure 2.1 Soil types within 200 km of Sydney (This map is available as a separate higher quality download from www.resource.nsw.gov.au)

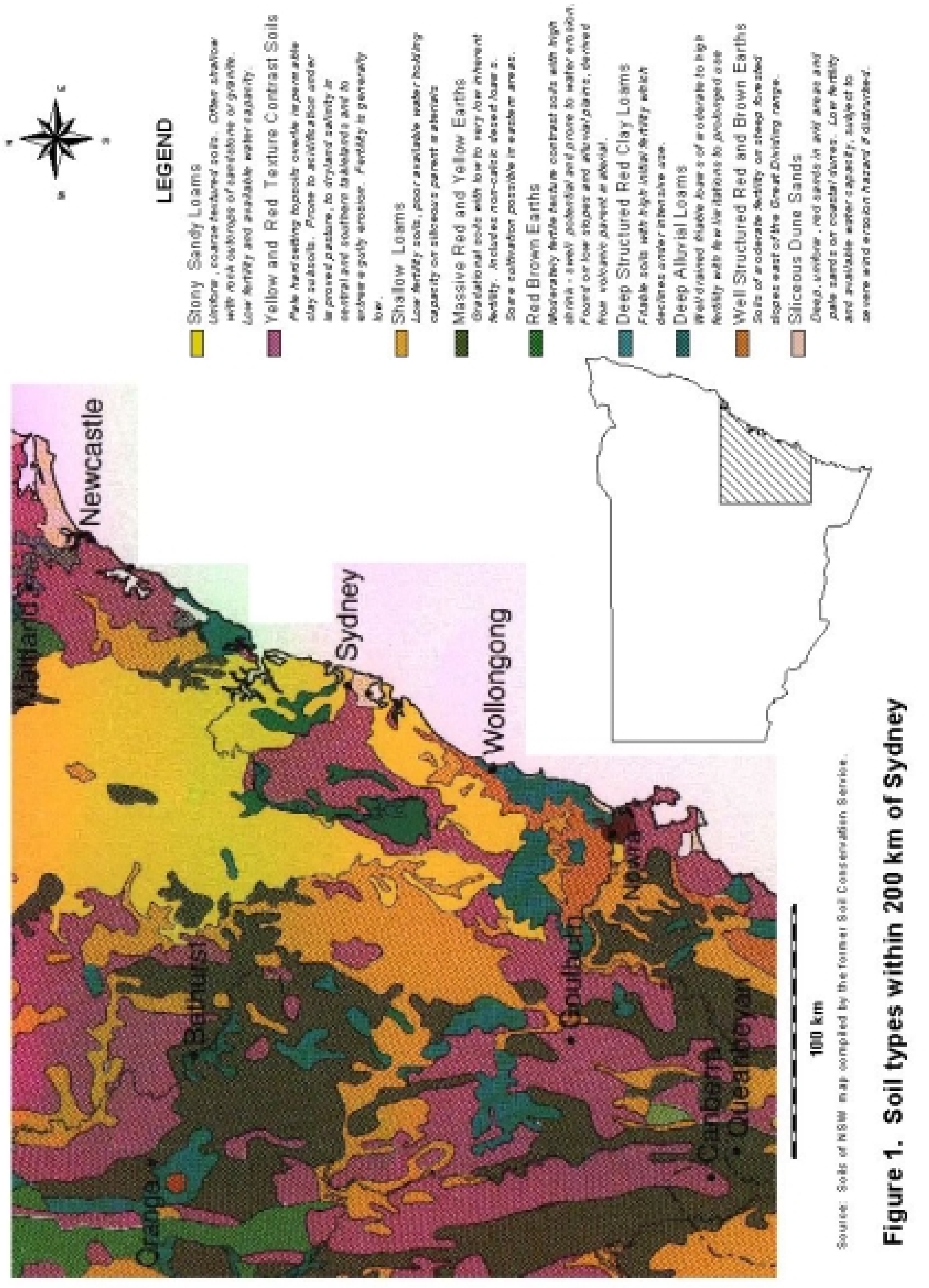

Table 2.2 Soil types and their properties within a 200-250 km radius of Sydney

Soil types	Approximate Australian soil classification[1]	Main properties
Stony sandy loams	**Tenosols**	Uniform, coarse textured, often shallow with rock outcrops. Low fertility and water holding capacity.
Yellow and Red textured contrast soils	**Podosols Sodosols**	Hard setting topsoils overlie impermeable clay subsoils. Prone to acidification under improved pasture, to dryland salinity in central and southern tablelands and to extreme gully erosion. Fertility is generally low.
Deep friable Red and Brown Clays	Vertosols	Well structured uniform texture soils of moderate fertility.
Shallow loams	**Tenosols**	Low fertility soils, poor available water holding capacity on siliceous parent materials.
Deep structured Red Clay loams	Vertosols	Friable soils with high initial fertility, which declines under intensive use.
Massive Black and Grey Coastal Clays	Vertosols	Alluvial clays of potentially high productivity but prone to waterlogging and local extreme acidification after draining
Massive Red and Yellow earths	**Kandosols Sodosols**	Gradational soils with low to very low inherent fertility. Some cultivation possible in eastern areas

[1]Soil types in bold are the dominant types in the RO target area

Soils within the target area for RO are dominated by lighter textured soils (based on clay content), with isolated areas of heavier clay soils in the Illawarra region and Central and Southern Tablelands (Figure 2.1). These soils tend to be shallow, have low inherent fertility and poor water holding capacity, and are prone to acidification, salinity, waterlogging and erosion. They also have a lower inherent capacity to sequester carbon compared to heavier soils (discussed in Section 4), consistent with the low natural organic carbon content of NSW soils by world standards (Charman and Roper, 1991). Thus, while large areas of low fertility agricultural soils exist in the target area for RO (Table 2.2), they are not ideal soil types to sequester carbon. The potential for these soils as carbon sinks is discussed further in Section 4.

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2.3 Recycled organics and their characteristics

The term "Recycled Organics" is a generic term for a range of products manufactured from compostable organic materials (garden organics, food organics, residual wood and timber, biosolids and agricultural organics) (ROU, 2001). In NSW, several RO products such as biosolids and liquid food organics are stabilised by chemical treatment or digestion and applied directly to land. Biosolids use in agriculture is regulated by EPA guidelines (NSW EPA, 1997), which defines product standards, application limits, site limitations and documentation. In 2000, 97% of biosolids produced by Sydney Water (Sydney Water, 2000) were used beneficially in agriculture, soil remediation and as a component of composts.

This review focuses on composted RO products, primarily derived from the garden organics and biosolids components of the RO stream. Compost quality is defined in Australia by an Australian Standard (Standards Australia, 1999), which prescribes aspects such as contaminant limits, stability and maturity criteria, and physical properties. Physical and chemical requirements for composted products according to Australian Standard AS 4454-1999 are given in Table A2 (Appendix). Composting is the process in which organic materials are pasteurised and microbiologically transformed under aerobic and thermophilic conditions for a period not less than six weeks. The composting process is not complete after this time and many products are then typically matured for a further period of 12 to 16 weeks under aerobic thermophyllic and mesophyllic conditions. The resultant products are stabilised materials, free of viable pathogens and weed propagules, with a high soil amendment value.

The composting process is essentially a controlled and more rapid version of the natural decomposition of organic material. The microbial, chemical and biochemical processes involved in composting are complex and beyond the scope of this review (see De Bertoldi, *et al*. 1986; Inbar *et al* 1990; Hoitink and Keener, 1992). The form of organic carbon in composted RO products is important for their potential role in soil carbon sequestration. In well-matured product in advanced stages of decomposition a high proportion of the organic carbon fraction exists as humic substances (Inbar *et al*., 1990) and could be considered to be equivalent to the more stable SOC fractions described in the literature (eg Baldrock and Skjemstad, 1999; Post and Kwon, 2000). These stable SOC fractions are important for aggregate stability and the retention of SOC (Tisdall and Oades, 1982; Martens, 2000) and will be described further in Section 3. The stabilised nature of organic carbon in composted RO products suggests their potential to enhance SOC levels when applied to soil. However, further chemical transformations and interactions with soil components are required before the organic carbon in composted RO products are fully integrated with the soil matrix and could be described as a component of SOC.

While many specific blends and mixes exist, there are two basic composted RO products defined by their end use (ROU, 2001): (1) Composted mulch is applied to soil surfaces and has at least 70% of its mass with a particle size of >15mm, and (2) Composted soil conditioners are suitable for incorporation into the soil and have at most 15% of its mass with a particle size of >15mm.

The chemical composition of composted RO products varies from batch to batch depending upon availability and chemical characteristics of particular raw materials. In the Sydney Basin, raw materials are typically garden organics and biosolids, but food organics are used by several small producers and mixed municipal solid waste (MSW) is used for RO production in some large scale in-vessel composting systems. Of significance to the potential of these products for SOC sequestration, organic carbon content can range between 20% and 30% (Fahy and Richard, 2000). Table 2.3 gives typical ranges for the chemical composition of composted RO products, based on data from 52 different products from Victoria and NSW (Wilkinson, *et al*., 2000).

Table 2.3. Selected Chemical Analyses of Composted RO Products (Adapted from Wilkinson *et al*.**, 2000)**

Characteristic	**Units[1]**	**N[2]**	**Mean**	**Median**	**Min**	**Max**
pH		49	7.3	7.3	5.6	8.3
Electrical Conductivity	dS/m	47	2.0	1.8	0.8	5.1
C/N Ratio		37	44	35	16	134
Nutrients (Total)						
Nitrogen	%(w/w)	47	0.88	0.86	0.39	1.6
Phosphorus	mg/Kg	41	1798	1650	500	4780
Potassium	mg/Kg	33	5326	4650	1896	11000
Sulphur	mg/Kg	23	1967	1850	840	2990
Calcium	mg/Kg	25	15158	15400	9000	20900
Magnesium	mg/Kg	25	3610	3610	1700	6170
Manganese	mg/Kg	19	199	210	54	300
Iron	mg/Kg	19	13881	14400	2100	21800
Boron	mg/Kg	19	25	24	15	45
Sodium	mg/Kg	29	1411	1300	709	2300
Heavy Metals (Total)						
Arsenic	mg/Kg	25	8	6	3	35
Cadmium	mg/Kg	29	0.6	0.5	0.4	**1.7**
Chromium	mg/Kg	26	60	51	8	**160**
Copper	mg/Kg	41	63	54	10	**165**
Lead	mg/Kg	41	92	81	21	**272**
Mercury	mg/Kg	25	0.2	0.2	0.1	0.4
Nickel	mg/Kg	24	23	18	5	62
Selenium	mg/Kg	21	0.9	0.6	0.5	2.4
Zinc	mg/Kg	41	**313**	**220**	73	**969**

[1]dry matter basis for nutrients and heavy metals
[2]number of samples tested (out of 52)
Figures in bold for heavy metals exceed AS 4454 limits.

Wilkinson *et al*., (2000) gives summary statistics for these data. The data in Table 2.3 do not distinguish between different types of composted products, which might explain some of the variations in nutrient and heavy metal content in particular. The data for nutrients also do not account for their availability for plant growth. A proportion of nutrients such as phosphorus and calcium has the potential to be bound within the organic matrix. A smaller data set from a compost manufacturer in the Sydney Basin with a high degree of process control (AS 4454 accredited) gives a much narrower range for these constituents, without the extremes of heavy metal concentrations (data not shown). On the basis of the data in Table 2.3, the potential fertiliser value of these products is notable, as is the observation that several of the heavy metal components exceed the limits defined by AS 4454. However, these levels of heavy metals are unlikely to result in excess heavy metal concentrations in soils because of dilution if the composts are incorporated. Repeated applications need to take into account the soil limits permitted in AS 4454 for these contaminants. However, there is also increasing recognition that a proportion of the heavy metals in composts is not readily mobile or available for plant uptake (Dumontet *et al*., 2001). In assessments of the benefits of composted RO products (Section 3), we assume in this review that heavy metal contaminant contents are within or near AS 4454 limits (see Table A2, Appendix).

Benefits of recycled organics as a soil amendment

This chapter discusses the potential of soil amendment with recycled organics to increase soil organic carbon and the consequent linkages to soil quality improvement

3.1 Recycled organics and linkages to soil quality

Soil quality is defined as "the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation" (Soil Science Society of America 1997). This definition portrays "a good quality" soil as a living and dynamic system, which is stable, resistant to stress and disturbance (buffering capacity) and with an ability to regenerate after disturbance (resiliance) (Van Bruggen and Semenov, 2000, Sherwood and Uphoff, 2000). This review will discuss the benefits of RO additions to soil on the three soil quality parameters: soil biological fertility (microbial biomass/function and mineralisation potential), chemical fertility (pH, EC, CEC, and nutrients) and physical fertility (soil porosity, aggregation, structure, bulk density, water holding capacity and hydraulic conductivity). The focus of the review will be on mechanisms involved in RO-mediated changes to soil properties. Potential adverse effects on soil quality of RO products that do not meet quality assurance standards are outside the scope of the review and will not be discussed. These include risks associated with the use of composts with excessive electrical conductivity and heavy metals (Bevacqua and Mellano, 1993; Illera *et al.*, 1999; Stamatiadis *et al.*, 1999)

The addition of RO products to soil directly contributes to the soil's nutrient status. However, the most significant benefit lies in their potential to restore and enhance soil quality parameters by adding biomass and increasing the SOC content through sequestration. Organic matter is a major determinant for the biological, physical and chemical fertility of soils (Charman and Roper, 1991) and consequently for soil productivity. Figure 3.1 shows the links between RO (biomass) inputs to soil, increased SOC, carbon sequestration and soil quality and emphasises their close interrelationships. Factors controlling SOC sequestration are discussed further in Section 4.

3.2 Potential of using recycled organics to increase soil organic carbon

A consequence of poor agricultural practices in the past is that many soils in NSW have lost more than half of their carbon stores (Dalal and Chan, 2001). Organic carbon is a significant component of RO and its application to soils should increase SOC levels (Pagliai *et al.*, 1981; Zinati *et al.*, 2001). While there are very few long-term experiments on the effect of RO application on SOC sequestration, the ability of RO to increase SOC is well illustrated by field trials at Rothamstead, UK where annual applications of 35 t/ha (fresh weight) farm yard manure from 1852 have increased SOC to over 3% compared to 1% in non-manured soil (Poulton, 1995).

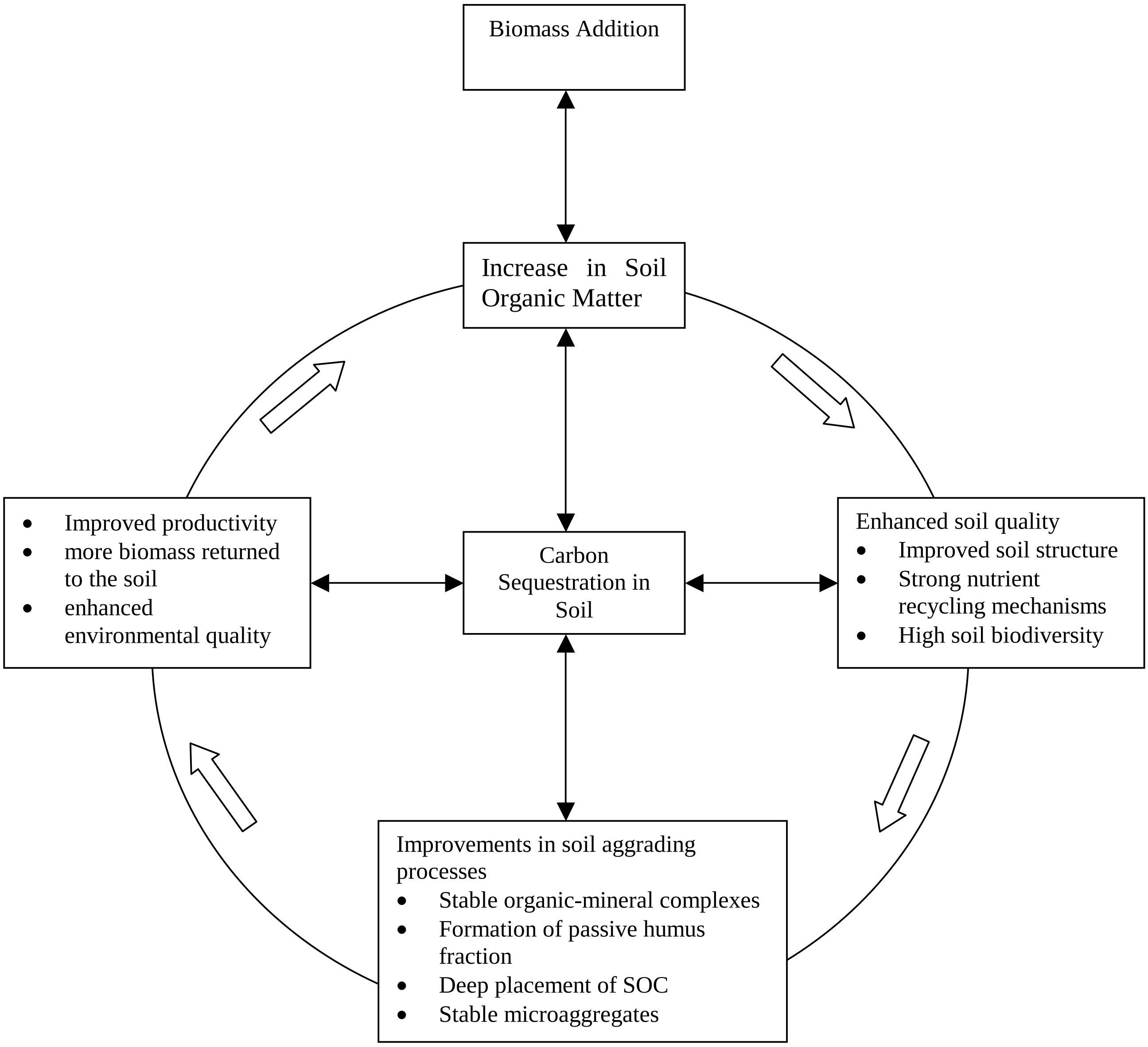


Figure 3.1 Relationship between carbon accumulation and soil quality (Source: Lal, 1997)

Increases in soil organic carbon after RO application for a number of short-term experiments reported in the literature are summarised in Table 3.1. The absence of published data from Australia is notable, though a number of studies have been conducted.

Table 3.1: Increases in SOC after soil amendment with RO

Application rate of RO (t/ha, product weight)	Soil/Soil texture	Duration of experiment (years)	Change in SOM (%)	Increase in SOM (%) per ton of added RO	Reference and location
120	Sandy silty loam	5	0.5 to 1	0.004	Albiach *et al.*, 2001 Spain
75	Coarse loam	2	1 to 1.1-1.85	0.001 to 0.01	Martens and Frankenberger ,1992 USA
327	Silty loam	3-4	1.58 to 4.22	0.008	Mays *et al.*, 1973 USA
128	Sand	1-2	1.35 to 2.06	0.005	Hortensine and Rothwell, 1973 USA
~150	Degraded arid soil	1	1.6 to 2.4	0.005	Illera *et al.*, 1999 Spain
2500	NA∗	4	1.6 to 4.9†	0.001	Mays and Giordano, 1989
74	Sandy loam	2	0.77 to 1.5	0.009	Bevaqua and Mellano, 1993 USA

† SOC was measured 15 years after compost additions
∗ NA = not available

Table 3.1 demonstrates that the application of each added ton of RO has the potential to increase soil organic matter (SOM) in the range of 0.001 to 0.01 %. This is equivalent to an increase in SOC of 0.0006 to 0.006% (assuming 1.72 as conversion factor from SOM to SOC by weight) after 1 to 5 years of application. Considering the different sources of RO (and hence different carbon composition), soil types, duration of experiment (short to medium term, 1-5 years) and geographic locations, it is difficult to draw many definitive conclusions from these results. However, assuming a soil bulk density of 1.3 Mg/m^3, the increases in SOC per ton of RO applied are equivalent to 0.008 to 0.08 t C/ha in the top 10 cm. The range of carbon sequestration rate is close to that reported for a low rate of manure (5 t/ha) (Fig. 3.2).

Furthermore, assuming a 50% moisture content and a carbon content of 30% for RO, the range of SOC increases measured in the soil corresponds to 5 to 50% of the carbon originally applied as RO. This is an extremely wide range partly reflecting the heterogeneous nature of RO used. Comparing this to the 4.6% carbon sequestration from stubble retention found by Heenan *et al.*, (1996) in experiments at Wagga Wagga, Australia after 20 years of crop/pasture rotation establishment, and the 15% carbon sequestration of plant residue quoted by Lal (1997), the range of carbon sequestration due to RO application is generally higher. This is probably due to the more resistant nature of the forms of carbon present in the RO because of the removal of the more labile C forms by the composting process (see Fig. 4.2, Section 4). The data for the sequestration of RO-derived carbon in soil is scarce and were determined in climatic conditions and soils that differ from those in NSW. Trials in NSW are necessary before the potential of RO to sequester soil carbon can be verified under local conditions and management practices.

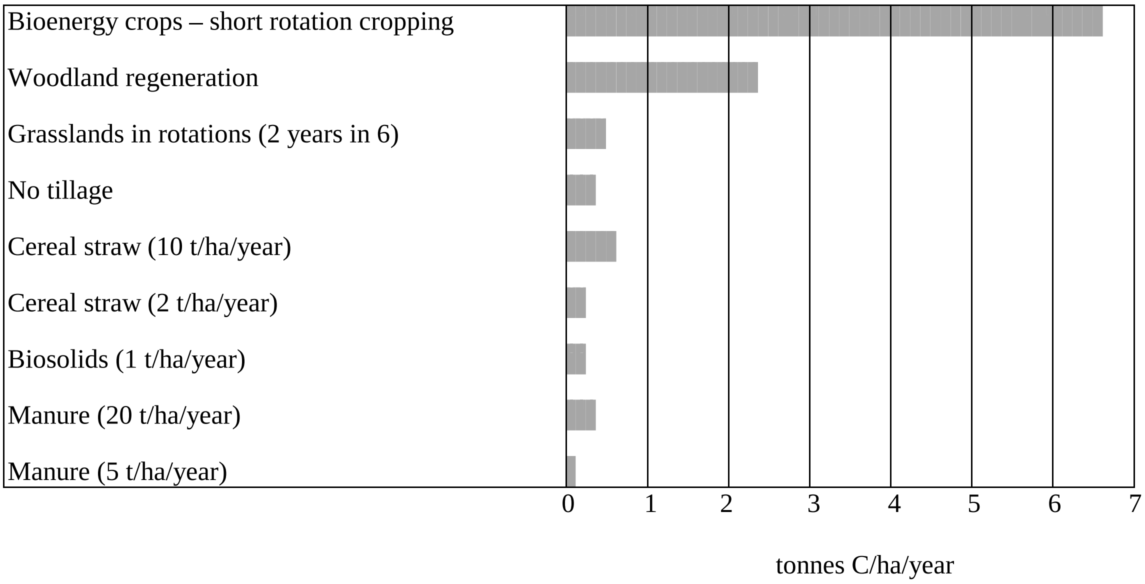


Figure 3.2 Carbon sequestration rate according to farm system amendments in Europe (modified from Pretty and Ball, 2001)

The changes in SOC as a result of RO application should be governed by the factors controlling SOC dynamics (climate, soil type and management practices) as outlined in Section 4.3. Additional factors include the nature (chemical composition) of the RO applied, which will influence the rate of subsequent carbon sequestration. For example higher SOC levels were found in MSW compost-amended soil when compared to biosolids compost, fertiliser and control treatments in a calcareous soil (Zinati *et al.*, 2001). These authors related the higher SOC to higher levels of the more stable, less oxidisable carbon forms of humin, humic acid and fulvic acid in the MSW compost-amended soil when compared to the other amendments. Furthermore, the method of application (incorporation or as mulch) will determine the rate of decomposition of any applied RO. Generally, when applied as mulch, RO will not be mixed with the soil and will decompose over a longer period than incorporated RO.

3.3 Improvement in soil biological properties

Organic residues of appropriate quality and quantity act not only as sources of nutrients and organic matter but also may increase the size, biodiversity and activity of the microbial populations in soil. Diverse populations of soil bacteria, fungi, protozoa and algae play a crucial role in soil quality and sustainability (Sherwood and Uphoff, 2000). They exploit a wide range of carbon substrates and are responsible for the decomposition of organic material, thus transforming, releasing and cycling nutrients and essential elements such as carbon (C), nitrogen (N) and phosphorus (P) from complex organic forms (Stirling, 2001).

Microbiological processes, and thus the rate of decomposition of organic matter applied to soil depend upon factors such as temperature, moisture, pH, aeration and availability of nutrients (Oades, 1988; Piao *et al.*, 2001). The chemical composition of the RO products, particularly their C/N ratios and humic acid content also influence their rates of decomposition (Inbar *et al.*, 1990; Sikora and Yakovchenko, 1996; Hartz *et al.*, 2000; Martens, 2000), the former because in products with excessive C/N ratios nitrogen can be immobilised and the latter because humic acid fractions are more resistant to decomposition than proteinaceous and carbohydrate fractions. These are important considerations for studies on RO decomposition, carbon sequestration and recycling of nutrients after RO application to soil.

The organic polymers in humified organic fractions of microbiologically decomposed organic matter act as binding agents for soil aggregate formation (Martens, 2000), an important determinant for good soil structure. Microbes can also benefit soil aggregation more directly either physically by fungal hyphal linkages or chemically by the production of polysaccarhides (or gums) that act as soil binding agents. These interactions are discussed in Tisdall and Oades (1982) and Oades (1984). Avnimelnich and Cohen (1988) stress the importance of aerobic conditions for the production of soil-stabilising molecules. The effects of the application of organic amendments on the biological properties of soil have thus become an active area of investigation due to the importance of these properties in soil function and structure (Albiach *et al.*, 2000).

Under natural soil conditions, fresh organic material is decomposed through several stages by a succession of microbial populations that utilise increasingly difficult carbon substrates from simple carbohydrates, to complex carbohydrates and to the resistant humus fractions (Stevenson, 1986). The result is a quantitative (biomass) and qualitative (diversity) change in microbial populations during the decomposition process. In composted RO, most of the labile fractions of organic carbon would be decomposed, with the more resistant lignified and humus fractions remaining (Inbar *et al.*, 1990, Sikora and Yakovchenko, 1996, Hartz *et al.*, 2000, Martens, 2000, see Section 4, Fig. 4.2). A number of investigations have shown soil amendment with RO influence microbial populations and enzymes related to microbial functions. A summary of these investigations is given in the Appendix (Table A3).

In most cases composted RO additions to agricultural soils or for the rehabilitation of mine site soils substantially increased microbial biomass. The increase results from the diverse microbial biomass contained in the added organic residue itself and from indigenous microbial responses to the increased availability and turnover of substrates within the added RO. Microbial increases have been measured either directly (Pera *et al.*, 1983; Guidi *et al.*, 1988; Press *et al.*, 2000), as biomass carbon (Perucci, 1993; Giusquiani *et al.*, 1994; Pascual *et al.*, 1999a; Garcia-Gil *et al.*, 2000) or by increases in soil respiration or substrate induced respiration which are indicators of microbial activity or potential activity (Rothwell and Hortenstine, 1969; Pascual *et al.*, 1999b; Emmerling *et al.*, 2000). However, heavy metal contaminants added with high rates of RO amendment have the potential to reduce the relative increases in microbial biomass (Garcia-Gil *et al.*, 2000) to the extent that the rate of SOC decomposition is inhibited (Dumontet *et al.*, 2001). This emphasises the need for care in the quality of RO products applied to agricultural soils to improve their fertility.

Because of their sensitivity to changes in soil conditions, trends in soil microbiological parameters have been proposed as potential indicators for long term trends in soil fertility (Sparling, 1992; Piao *et al.*, 2001) and of soil ecological stress and degradation (Dick and Tabatabai, 1992). The classes of microbes identified as responding to RO applications were typically cellulolytic microbes, actinomycetes and mycorrhiza (Rothwell and Hortenstine, 1969; Pera *et al.*, 1983; Guidi *et al.*, 1988) which are important in processes for organic matter decomposition. Microbial populations shift initially from largely bacterial populations to populations dominated by fungae and actinomycetes at later stages of organic matter decomposition (Rothwell and Hortenstine, 1969; Pera *et al.*, 1983) probably because of changes in the nature of microbial substrates (including carbon sources) and moisture conditions.

Measurements of specific soil microbial enzyme activities are useful because they are indicators of the potential for specific reactions important for carbon and nutrient cycling, or of microbial metabolism, rather than simply of microbial presence. Several studies have demonstrated long term (up to eight years) increased activities of hydrolytic enzymes in soils after amendment with RO. For example Albiach *et al.* (2000) found increases in dehydrogenase, alkaline phosphomonoesterase, phosphodiesterase, arylsulphatase and urease four and five years after soil amendment with 24 t/ha/yr of MSW compost, biosolids and manure. Different levels of enzymes in different treatments reflected the different chemical composition of the organic amendments. Enzyme activities respond differentially to heavy metal loads added in the RO amendment and to the lability (ease of mineralisation) of the carbon substrates (Garcia-Gil *et al.*, 2000). This can complicate the interpretation of enzymic responses to RO amendments.

Similar trends of increased soil enzyme activities were found by Guisquiani *et al.* (1995) four years after incorporation of up to 90 t/ha/yr of MSW compost with soil. High correlations of several biochemical parameters with soil porosity were interpreted as indicating an improvement in soil physical fertility from the RO treatments. Several other studies also report increased activities of soil hydrolytic enzymes after RO amendment (Garcia *et al.*, 1994; Pascual *et al.*, 1999b; Emmerling *et al.*, 2000).

The direct effect of greater and more diverse microbial populations in RO-amended soils is the long term nutrient cycling from applied organic matter and the improved soil aggregation characteristics related to microbe-derived binding agents. Diverse microbial populations in RO products and the influence of RO amendments on soil microbial populations have also been implicated in the suppression of soil-borne plant diseases (Hointink and Fahy 1986; de Ceuster and Hointink 1999a,b). Numerous studies cite reduced incidences of diseases such as *Pythium*, *Botryis* and *Fusarium* (Wong, 2001) and suppressive composts are now proposed for use commercially to fully or partially replace chemical treatments (Anon., 1997; de Ceuster and Hointink, 1999b). The mechanisms for suppression are complex and are proposed to include antibiotic or chemical inhibitor production, induction of localised or systemic resistance in the plant or simply competition for nutrient and carbon sources in the soil (Hointink and Fahy, 1986; Wong, 2001). All composts are not equally disease suppressive and the suppression is dependent upon factors such as temperature, moisture, pH and compost maturity (de Ceuster and Hointink, 1999a; Wong, 2001). Well-matured composts with large and diverse populations of mesophyllic microbes tend to be highly suppressive (Hointink and Boehm, 1999; Wong, 2001). Some researchers have produced highly suppressive composts by adding microbial antagonists such as *Trichoderma, Flavobacterium* and *Enterobacter* species (Hointink and Boehm, 1999).

While not the focus of this review, the rich microbial biomass and diversity of compost matrices are also important in strategies to bioremediate contaminated soils (reviewed by Semple *et al.*, 2001). These xenobiotic microbes can be effective in degrading otherwise recalcitrant pollutants to innocuous or less harmful metabolites.

3.4 Improvement in soil physical properties

Soil physical properties, such as soil moisture characteristics and hydraulic properties, bulk density and soil porosity can be linked to one of the most fundamental of soil properties, soil structure. Soil structure is the architecture of the soil, describing the size, shape and arrangement of soil particles or aggregates and the voids between them (Chan, 2001). A soil with good structure and stable aggregates will exhibit desirable values of bulk density and porosity for a given soil type that promotes adequate soil aeration and available water. A well-structured soil will also display no surface crusting, and have infiltration characteristics and hydraulic conductivity properties that minimise runoff but retain water for plant use. These characteristics define the physical environment of the soil ecosystem and are critical for a healthy soil and sustainable agriculture. Notably, soil structure has been adversely affected by inappropriate soil management practices in many tillage-based agricultural production systems.

Enhanced soil structural properties are linked with increased SOM (Tisdall and Oades, 1982) and the literature contains considerable evidence that a range of RO amendments (composts or biosolids) increases the organic matter of soil (Khaleel *et al.*, 1981; Albiach *et al.* 2001; Zinati *et al.*, 2001; also see Table 3.1). These increases are often accompanied by improvements in soil aggregate stability (Gallardo-Lara and Nogales, 1987; Martens and Frankenberger, 1992) and physical parameters such as bulk density and porosity, water holding capacity and infiltration (Khaleel *et al.*, 1981; Pagliai *et al.*, 1981; Gallardo-Lara and Nogales, 1987; Martens and Frankenberger, 1992; Shiralipour *et al.*, 1992a ; McConnell *et al.*, 1993; Turner *et al.*, 1994; Stockdale *et al.*, 2001). Tables 3.2 and 3.3 give the changes associated with RO amendments for soil bulk density and water content respectively in a limited number of studies. Recycled organics application decreases soil bulk density (increased porosity) and increases soil water holding capacity. Significantly, the results in Table 3.3 were based on gravimetric soil water content rather than the water available for plant uptake. These are quite distinct soil characteristics and are discussed in more detail below. Table A4 (Appendix) gives more details of the literature reporting the effects of RO amendments such as MSW and biosolids-based composts on soil physical characteristics. Comprehensive summaries of other studies are also given by Khaleel *et al.* (1981) and Shiralipour *et al.* (1992a). Direct comparisons of effects are often difficult because of the variability in RO products and in the test soils used in different studies (Albiach *et al.*, 2000). The effects of RO mulch treatments will also differ from RO treatments incorporated into the soil. The initial effects of the former on the soil properties would primarily be restricted to surface effects at the soil/RO interface until further decomposition and natural mixing had taken place, and to insulation effects against extremes in soil temperatures.

Table 3.2 Decreases in topsoil bulk density after soil amendment with RO

Application rate of total RO t/ha	Soil/Soil texture	Duration of experiment (years)	Change in bulk density (g/cm^3)	Decrease in bulk density (g/cm^3)	Reference and location
134	Fine sand	2	1.3 to 1.1	0.2	Turner *et al.*, 1994 USA
75	Coarse loam	2	1.48 to 1.32	0.16	Martens and Frankenberger, 1992 USA
180	Coarse textured loamy sand	4	1.67 to 1.41	0.26	Zebrath *et al.*, 1999 Canada
44	Silty clay loam	1	1.15 to 1.08	0.07	Stamatiadis *et al.*, 1999 USA
327	Silt loam	3-4	1.37 to 1.12	0.25	Mays *et al.*, 1973 USA
80	Degraded arid soil	1	1.22 to 1.06	0.16	Illera *et al.*, 1999 Spain
Rate equivalent to the addition of 3% dry matter	Compacted clay	laboratory	1.58 to 1.36	0.22	Avnimelech and Cohen, 1988 USA

Table 3.3 Increases in topsoil soil water content after soil amendment with RO

Application rate of total RO t/ha	Soil/Soil texture (years)	Duration of experiment (years)	Change in soil water content (g/100g, %)	Increase in water content (% weight basis)	Reference and location
75	Coarse loamy	2	10 to 11-13	1 to 3	Martens and Frankenberger, 1992 USA
60	Clay sand	laboratory	17.23 to 24.77	7.54	Hernando *et al.*, 1989 Spain
44	Silty clay loam	1	13.7 to 15.0	1.3	Stamatiadis *et al.*, 1999 USA
50 to 100	Silty loam	2		Increased by 6 to 7%	Movahedi and Cook, 2000 UK
15	Fine sandy loam	2	15 to 17.1	2.1	Edwards *et al.*, 2000 Canada
327	Silt loam	3-4	12.4 to 14.8	2.4	Mays *et al.*, 1973 USA
80	Degraded arid soil	1	7.7 to 11.6	3.9	Illera *et al.*, 1999 Spain

Mechanisms for Soil Structural Improvements from RO Amendments

Aggregate stability. Many of the improvements in soil structural parameters measured in RO-treated soils are interrelated and can be linked to improved water-stability of soil aggregates. A soil aggregate is 'a naturally occurring cluster……. of soil particles in which forces holding the particles together are stronger than the forces between the adjacent aggregates' (Martin *et al.*, 1955). The role of organic matter in aggregate stability is complex (Albiach *et al.*, 2001), but is associated with the binding properties of persistent humic acids and microbial-derived carbohydrates and gums (Tisdall and Oades, 1982; Martens and Frankenberger, 1992; Albiach *et al.*, 2001; Watts *et al.*, 2001). Consequently, soils amended with RO products, which increase organic matter and stimulate microbial numbers and diversity (Section 4.3) would be expected to display improved soil aggregate stability.

Overall soil aggregate stability measured for a given soil is a function of the interactions between organic and mineral (clay, calcium, aluminosilicates and hydrous oxides) binding soil components and environmental factors such as soil aeration (Avnimelech and Cohen, 1988) and temperature (Albiach *et al.*, 2001). This complexity of factors might explain the absence of increased aggregate stability in RO-treated soils reported by some studies (Guidi *et al.*, 1988). Also, while the positive effects of organic amendments to soil on aggregate stability are demonstrable and well acknowledged, the formation of stable aggregates is a gradual process (Martens and Frankenberger, 1992). Composted RO amendments to soil will not necessarily provide immediate aggregate stability to poorly structured soils.

Porosity, pore size distribution and infiltration. Many of the soil physical properties rely upon the presence of stable aggregates of 1-10mm to ensure a distribution of pore sizes between these aggregates. The pores can be classified by size as storage pores (0.2-30μm diameter), important for water retention through the forces of surface tension, and transmission pores (>75μm diameter), important for infiltration and drainage and hence ensuring that the soil remains aerobic (Pagliai *et al.*, 1981; Tisdall and Oades, 1982). The improvement in soil aggregate stability measured in RO-amended soils is reflected by increases in porosity (Pagliai *et al.*, 1981) and increased infiltration rates (Khaleel *et al.*, 1981; Martens and Frankenberger, 1992). However, the magnitude of change is dependent upon the initial texture of the amended soil. Recycled organics applied to light textured (sandy) soils is more likely to increase the proportion of storage pores and reduce water infiltration and transmission properties (Kumar *et al.*, 1985).

Bulk Density. Bulk density is the oven dry weight of soil per unit volume, expressed as Mg m^{-3}. It is closely linked with porosity and to the ability of plant roots to penetrate the soil profile. While critical values for bulk density vary with soil texture, a moderate range for the parameter is 1.3-1.6 Mg m^{-3} (Hazelton and Murphy, 1992).

Decreased bulk density initially measured in RO-amended soils is most likely a simple dilution effect of the denser mineral fraction of the soil, though the effect can be sustained after most of the organic matter has decomposed (Martens and Frankenberger, 1992; Shiralipour *et al.* 1992a). This might be related to the influence of humic acids on soil aggregration. The effect is also more pronounced for coarse textured soils and is linearly related to increases in SOC from RO treatment (Khaleel *et al.*, 1981).

Soil Moisture Retention. Many studies have demonstrated increased moisture retention (or water holding capacity) in soils amended with RO (Khaleel *et al.*, 1981; Kumar *et al.*, 1985; Hernando *et al.*, 1989; Martens and Frankenberger, 1992; Turner *et al.*, 1994; Illera *et al.*, 1999; Zebarth *et al.*, 1999). Although differences in the extent of soil moisture retention are reported in soils of different textural classes, regression analysis has shown that SOC is a major determining factor (Khaleel *et al.*, 1981).

The mechanisms involved include improved porosity and pore size distribution, with increases in the relative number of storage pores (Shiralipour *et al.*, 1992a), and the colloidal nature and increased surface area of the RO amendment (Khaleel *et al*., 1981; Zebarth *et al*., 1999), which retain water. However, although the capacity to store water can increase in RO-amended soils, the water available for extraction by plants (available water capacity - AWC) is often reported to be unchanged (Khaleel *et al.*, 1981; Turner *et al.*, 1994). This apparent anomaly occurs because RO-amendment *per se* does not change the shape of the moisture characteristic of a soil (a fundamental property of soils that defines AWC), and simply increases measured water content at different moisture potentials. Increases in AWC in RO-amended soils might occur over time through secondary effects on soil structure, which would change the shape of the moisture characteristic.

The conflict between water soil water content and soil water availability has implications for studies aiming to demonstrate the benefits of RO-amendments for the moisture characteristics of agricultural soils. Long-term field studies on RO-soils with different textural classes under differing climatic conditions are needed to clarify these issues.

3.5 Improvements in soil chemical fertility

Composted RO products contain nutrients such as nitrogen (N), phosphorus (P) and a number of micronutrients in higher concentrations than in agricultural soils (McConnell *et al.*, 1993). Thus they have a demonstrable fertiliser value and have been used to replace or partially replace inorganic fertilisers to increase soil N (Gallardo-Lara and Nogales, 1987; Buchanan and Gliessman, 1991; Iglesias-Jimenenez and Alvarez, 1993; Garcia *et al.*, 1994; Maynard, 1999), available P and exchangeable potassium (K) (Pinamonti *et al.*, 1995; Pinamonti, 1998) and extractable P (Neilsen *et al.*, 1998), K, calcium (Ca), and magnesium (Mg) (Mays *et al.*, 1973). The agronomic benefits found in many of these studies are summarised in Table 3.4, with more detail given in Table A5 (Appendix). Many other examples are given in Gallardo-Lara and Nogales (1987) and Shiralipour *et al.* (1992b).

The studies in Table 3.4 suggest that crop yields increase with increased RO application. However, responses are variable and are not necessarily due to a fertiliser effect only. For example, yield increases on fine textures soils were greater than on sandy soils (Maynard, 1999). Other studies reported no crop response to RO application, ascribed to the high natural fertility of the test soils (Gallardo-Lara and Nogales, 1987; Stamatiadis, *et al.*, 1999), positive responses only when fertiliser amendment rates were less than optimal (Fauci and Dick, 1996) or responses in some years compared to fertilised controls but not in others (Pinamonti *et al.*, 1995).

Nutrient Availability. An important aspect of the nutrients in composted products is their availability for plant uptake. The maturity of composted product is of particular importance for the availability of nutrients such as N (Bernal *et al.*, 1998; Mamo *et al.*, 1999). Fully matured composts contain a significant proportion of its N in readily available forms (nitrate and ammonium) (Iglesias-Jiminez and Alvarez, 1993; Eriksen *et al.*, 1999). Continued decomposition of more stable organic N sources over a sustained period regulates the subsequent mineralisation of available N in soil (Gallardo-Lara and Nogales, 1987) which is balanced by partial biological immobilisation by soil microbes (Iglesias-Jiminez and Alvarez, 1993). This balance provides a residual source of N available for plant uptake.

By contrast, immature composts with high C/N ratios (>40) will tend to withdraw available N from the soil to meet the demands of the decomposing microbes and cause crop N deficiencies (Gallardo-Lara and Nogales, 1987; Eriksen *et al.*, 1999; Mamo *et al.*, 1999).

Table 3.4 Increase in crop yields after soil amendment with RO

Application rate of RO t/ha	Soil/soil texture	Duration of experiment (years)	Change in crop yields	Increase in crop yield	Reference and location
50	Ferrallitic	Pot study	**Perennial ryegrass:** 8 to 16 g/pot	8 g/pot	Iglesias-Jimenez and Alvarez, 1993 Spain
512	Spodosols	Pot study	**Oats:** 26 to 52 g/pot **Radish:** 27 to 187 g/pot	26 g/pot 160 g/pot	Hortenstine and Rothwell, 1968 USA
128	Sand	Pot study	**Sorghum** Crop 1: 11.2 to 26 g/pot Crop 2: 1.4 to 39.6 g/pot	14.8 g/pot 38.2 g/pot	Hortenstine and Rothwell, 1973 USA
10	Loamy sand	1	**Sorghum:** 408 to 1380 kg/ha grain	972 kg/ha	Ouedraogo *et al.*, 2001 Burkina Faso
74	Sandy loam	2	**Onion:** 11 to 166 g/plant fresh wt **Turf:** 62 to 496 g/plant fresh wt **Turf:** 32 to 76 g/plant fresh wt	155 g/plant 434 g/plant 44 g/plant	Bevaqua and Mellano, 1993 USA
30	Sandy loam	NA*	**Broccoli:** 2226 to 5080 kg/ha dry weight	2854 kg/ha	Buchanan and Gliessman, 1991 USA
7.5 cm mulch layer	NA*	NA*	**Grapevines:** 0.8 to 2.5 kg/vine	1.7 kg/vine	Buckerfield and Webster, 1999 South Australia

*NA = not available

The existence of available and residual N forms in mature, composted RO products could be used to advantage in crop nutrition, with an initial, short-term store of available N (nitrate and ammonium) provided at the time of RO application and gradual release of residual N during subsequent growing seasons. The potentially high initial available N in mature composted products suggests that application rates should not exceed agronomic rates (based on N content and estimated mineralisation rate) so that nitrate leaching to groundwater is avoided (He *et al.*, 2000; Buchanan and Gliessman, 1991; Iglesias-Jiminez and Alvarez, 1993). This is the approach taken by regulatory guidelines for the application of RO products such as biosolids to agricultural land (NSW EPA, 1997). However, supplementation of RO products with inorganic N fertilisers may be necessary to meet the N needs of some crops (Eriksen *et al.*, 1999; Sikora *et al.*, 2001), or on light textured soils (Maynard, 1999).

Factors that affect the extent of N mineralisation in RO are complex, and include soil type, pH, climatic conditions, RO application rate and type or maturity of the RO product (Eriksen, *et al.*, 1999; Mamo *et al.*, 1999). He *et al.* (2000) reported the proportion of inorganic N derived from the mineralisation of organic matter in RO treatments (mineralisable N) of from 23% for composted yard waste and co-composted yard waste and biosolids, to over 48% for biosolids. In glasshouse experiments, Iglesias-Jiminez and Alvarez (1993) reported from 16 to 31% mineralisable nitrogen and Hartz *et al.* (2000) reported an average of 17% mineralisable N after six months for a range of compost and manure samples. By contrast, less than 5% of soil N was mineralised 120 days after various treatments with MSW composts (Mamo *et al.* 1999), though the potentially mineralisable N (acid extractable) ranged from 43% to 63%. This would represent a residual store of N in subsequent growth seasons.

Cation exchange capacity (CEC). The CEC of a soil is its capacity to retain and exchange cations from active exchange sites on colloidal and organic components of soils. CEC is commonly measured as the sum of exchangeable Ca, Mg, K, sodium (Na) and aluminium (Al) cations present per unit weight of soil. The level and balance of these ions are important factors in structural stability, nutrient availability, pH and the soil reaction to fertilisers and other amendments (Hazelton and Murphy, 1992).

Mature composted RO products may exhibit CECs of >30 cmol+/kg (Garcia *et al.*, 1991) and increases soil CEC when applied at high rates (Table 3.5). As with many other beneficial effects of RO applied to soil, increases in CEC are dependent upon soil texture, with sandy soils the most responsive (Shiralipour *et al.*, 1992a; McConnell *et al.*, 1993).

Table 3.5 Increases in CEC after soil amendment with RO

RO Application rate (t/ha)	Soil/Soil texture	Duration of experiment	Change in soil CEC (cmol+/kg)	Increase in soil CEC (cmol+/kg)	Reference and location
1000	various	Various, up to 19 years	6.9 to 14.6	7.7	Anonymous 1993 USA
512	Spodosols	Pot study	4.05 to 8.28	4.23	Hortenstine and Rothwell, 1968 USA
128	Sand	Pot study	3.47 to 4.52	1.3	Hortenstine and Rothwell, 1973 USA
10	Loamy sand	1	4 to 6	2	Ouedraogo *et al.*, 2001 Burkina Faso
2500 625		14 14	6.9 to 14.6 6.9 to 10.5	7.7 3.7	Mays and Giordano, 1989
200	Loamy sand	4	Limited effect	N/A	Zebarth *et al.*, 1999 Canada

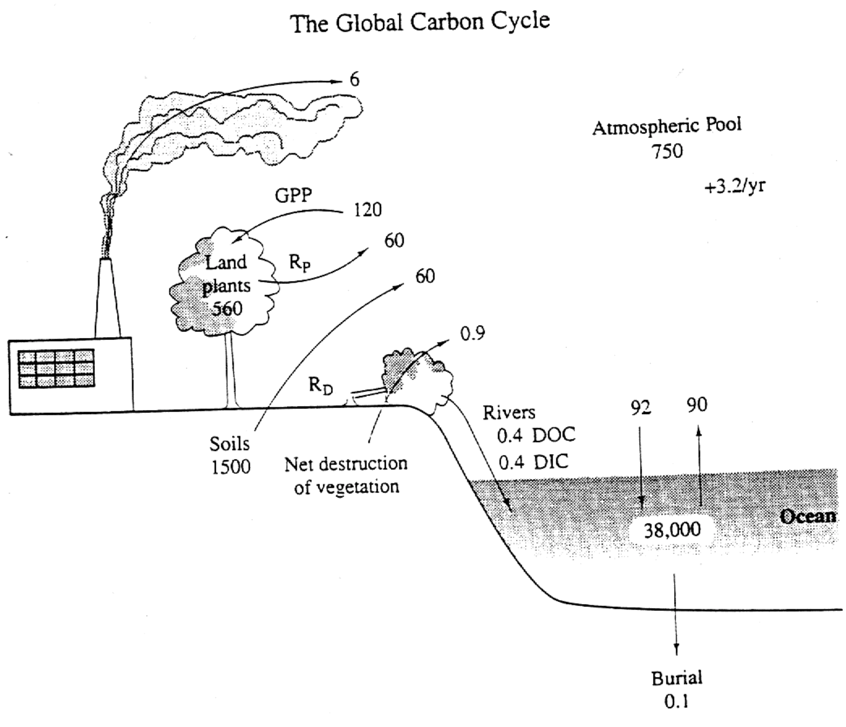
Amelioration of problem soils using RO: The potential benefits in enhancing soil physical, chemical and biological properties discussed above and the resultant improvements in plant growth and production, opportunities exist for using RO products as soil amendments. Many NSW soils have inherent problems such as salinity, sodicity and acidity (Northcote, 1983). These soil problems have also been created in many areas by past poor management and other human activities e.g. mining. The suitable approach for RO product use in these situations is to enhance plant growth and establishment by providing a more favourable soil environment, so starting the bio-remediation process. Currently, few RO products are being used for this purpose.

Soil organic carbon and the carbon sequestration potential of NSW soils

This chapter discusses soil organic carbon, its role in agroecosystems, composition, dynamics in soils, and the potential for carbon sequestration in NSW soils.

4.1 Soil organic carbon and the global carbon cycle

Soil organic carbon is an important component of the global carbon cycle (Fig. 4.1), which describes the different carbon reservoirs and the carbon flows or fluxes between them. In the context of global warming and carbon sequestration, the primary interests are carbon reservoirs in the atmosphere, land plants and soil, and in the mass flows of carbon between these reservoirs.



All pools and fluxes are expressed in units of 10^{15} g C/yr, averaged for the 1980s
GPP-gross primary production; **Rp**-plant respiration; **R_D**-respiration from decomposed materials; **DOC**-dissolved organic carbon; **DIC**-dissolved inorganic carbon

Figure 4.1. The global carbon cycle (Source: Schlesinger, 1996).

Plants on land adsorb CO_2 from the atmosphere through photosynthesis (GPP in Fig. 4.1). The terrestrial biosphere returns carbon to the atmosphere through plant respiration (Rp) and the decomposition of plant residues (R_D). The uptake and loss of carbon by land plants and soil were closely balanced before human intervention (Schlesinger and Andrews, 2000). The clearing of land for human activities accelerates the transfer rate of carbon from the terrestrial system to the atmosphere. Fossil fuel burning transfers carbon from the geological reservoir to the atmosphere. The atmosphere is one of the smaller reservoirs but is the subject of concern in the context of global warming. Carbon dioxide is the most important greenhouse gas. There have been significant increases in atmospheric CO_2 concentrations since the Industrial Revolution and the current rate of increase is estimated to be 0.5 % yr^{-1} (Swift, 2001). The increases in atmospheric CO_2 are related to increases in fossil fuel burning, the clearing of land for agriculture and urban development in the last 150 years (Post *et al*., 1990; Swift, 2001).

There are various estimates of the size of the different carbon reservoirs making up the global carbon cycle (Kimble *et al*., 1990; Post *et al.,* 1990; Rosell and Galantini, 1998). As indicated in Fig. 4.1, the carbon contained in soils (~1500 Pg , 1 Pg = 10^{15} g) is more than twice that of the atmosphere and is three times that in the biotic pool of all living matter. Furthermore, the amount of carbon released from the soils per annum (via respiration) is more than 10 times than that from fossil fuel burning (Fig. 4.1) Both highlight the potential important role soil can play as a sink for atmospheric carbon and therefore in combating global warming (Lal, 1997; Rosenzweig and Hillel, 2000; Izaurralde *et al.,* 2001). However, to achieve this would require better management of carbon in the soil. In turn, it would require a better understanding of the role of SOC, its composition and the factors controlling the carbon sequestration processes in soils.

4.2 Soil organic carbon, its importance, composition and different soil organic carbon pools

Soil organic carbon refers to the carbon present in soil organic matter (SOM). The latter is the heterogenous mixture of organic substances present in soils representing the products at all stages of decomposition of plants, animals and microbes. The elemental composition of SOM consists of about 50% C with lesser amounts of oxygen (O) and hydrogen (H) plus small quantities of N, P, sulphur (S) and many other elements. It is difficult to measure SOM content directly because of variations in the content of its component elements (C, H, O, N, P and S) (Baldock and Skjemstad, 1999). Therefore most analytical methods determine the concentration of SOC which can then be converted to SOM using a typical conversion factor of 1.72.

Soil organic matter is a fundamental component of the soil that controls the chemical, physical and biological aspects of soil quality (Chan, 2001). The important ecosystem roles played by SOM have been summarised by various authors (Volk and Loeppert, 1982; Charman and Roper, 1991; Fisher, 1995; Skjemstad, *et al.*, 1998) and include:

- Source of carbon and energy for soil micro-organisms,
- Cation exchange capacity which affects the retention (prevents the leaching of essential plant nutrients), release and availability of plant nutrients ,
- Major source of and a temporary sink for plant nutrients (such as N, P and S),
- Improvement in soil buffering capacity, against acidification and toxicities
- Formation and maintenance of desirable soil structure,
- Improvement of water percolation into and retention by the soil,
- Absorption of solar radiation which influences soil temperatures,
- Ability to stimulate plant growth.

Formation of SOC from plant and animal residues is a complex phenomenon that includes the decomposition, humification, accumulation and distribution of the various organic substances within the soil profile. Soil organic carbon is made up of a continuum of soil organic compounds in terms of the ease of their decomposition and turnover time.

Fig.4.2 represents the conversion of organic residues to SOC during the stages of decomposition. With successive decomposition, the more easily decomposed substances are lost to the atmosphere as CO_2, and the remaining compounds are further transformed chemically and biologically (the process of humification). The rate of decomposition of different plant residues depends upon the C:N ratio and resistance to decomposition on the lignin content (Rahn and Lillywhite, 2002). Thus wheat with a C:N ration of 58 will decompose more slowly that vegetable residues (C:N 4-9) (Rahn and Lillywhite, 2002). The SOC present in the soil at any time consists of a complex mixture of organic compounds representing products at different stages of decomposition and only a portion of the input organic material is eventually converted to the stable form of SOC, commonly known as humus. Lal (1997) used 15 % as the percentage of crop residue that would be converted to stable form of SOC. However, long-term trial results from Wagga Wagga, New South Wales suggest that this conversion factor was only 4.6 % (Heenan *et al*., 1996).

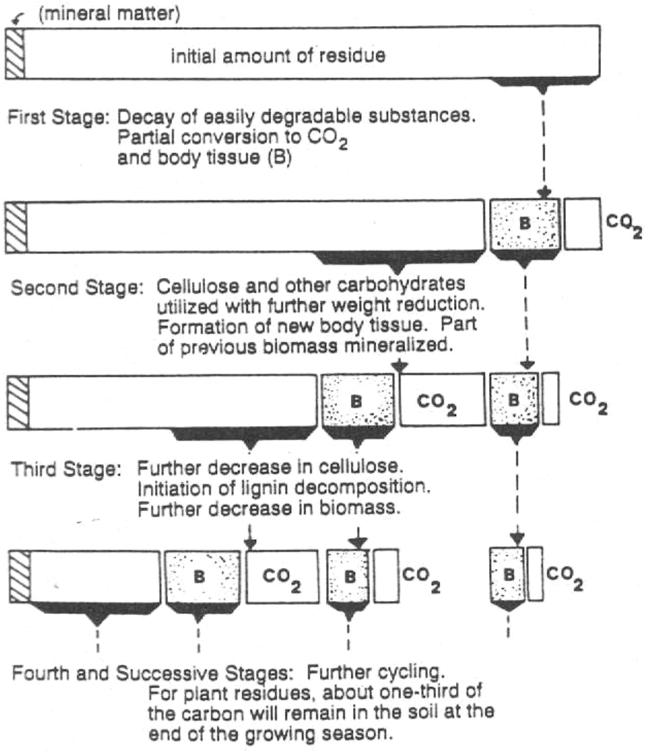


Figure 4.2 Decomposition of organic material and conversion to SOC at different stages (Source: Stevenson, 1986).

Because of its complexity, for modelling purposes SOC is conceptually divided into a number of pools based on their turnover rates (lability). For example:

- Jenkinson and Rayner (1977) divided soil carbon into active, slow and passive pools with different turnover times (2 to 1980 years)
- Campbell (1978) divided SOC into labile and stabilised fractions with turnover times of 53 and 1429 years respectively
- Paul and van Veen (1978) divided SOM into recalcitrant and decomposable fractions.
- Parton *et al.* (1987) divided SOC into three pools - active, slow and passive, with turnover time of 1.5, 25 and 1000 years respectively

Table 4.1 Soil organic carbon pools and the factors controlling their pool sizes (Source: Eshwarn *et al.*, 1995)

	Carbon pools in the soil	Controlling factors	Agronomic factors
1	Active or labile pool. Readily oxidized	Residue inputs and climate	Management affects the size of the pool
2	Slowly oxidized pool Macro-aggregrates	Soil aggregates and mineralogy	Management particularly tillage affects the size of this pool
3	Very slowly oxidised pool Micro-aggregates	Water stable micro-aggregates	Have little impact on this pool
4	Passive or recalcitrant pool	Clay mineralogy (as complexes of clay minerals); microbial decomposition may have reduced carbon to elemental form	Do not influence this pool

Division of SOC into different pools is necessarily arbitrary and usually based on their different turnover times. In reality, they represent different forms of organic carbon compounds and some are very resistant to decomposition (i.e. long turnover time). Resistance of SOC to decomposition can be due to chemical as well as physical factors. Skjemstad *et al*. (2001) give two examples of chemical forms of resistance to decomposition. SOC declined much more slowly in one soil type (Waco soil) than the other (Langlands-Logie soil). The authors concluded that the difference was attributable to the higher aromaticity (existence as cyclic carbon compounds) of the SOC of the former soil. Aromatic carbon was resistant to decomposition for 50 years (Skjemstad *et al.,* 2001). Another example is that of charcoal often reported as a component of SOC but is an inert form of organic carbon. Thus it is unlikely to play an active role in carbon dynamics (Skjemstad *et al.,* 2001).

Resistance to decomposition can also be conferred to otherwise labile organic carbon by physical factors. This protection can occur in two ways: (i) by adsorption of organic components on to soil mineral surfaces, and (ii) by occlusion within soil structural units (micropores) (Jenkinson, 1988). Both mechanisms provide protection against decomposition by microbes. As shown in Table 4.1, carbon in the slow decomposing pool (2) is closely associated with the mineral fractions of the soils, either as complexes with the clay minerals or by its location within microaggregates. The SOC in this and the active (1) pool, is strongly affected by management practices such as tillage. Importantly, the carbon forms in pool (2) are essential constituents of stable soil aggregates and hence of good soil structure (Six *et al*., 2000). The SOC in more resistant pools (3) and (4) is chemically and/or physically protected and less readily impacted by agronomic practices (Table 4.1).

Another reason to consider SOC in terms of different pools is that from a soil management perspective. Small changes in total SOC are often difficult to detect because of natural soil variability and background carbon levels (Blair *et al.*, 1995). Therefore, many attempts have been made to differentiate SOC into various pools of varying lability and the more labile pools have been used as sensitive indicators of changes in response to land use management (Blair *et al*., 1995; Chan *et al*., 2001a).

4.3 Factors controlling soil organic carbon levels

Soil organic carbon levels are dependent on a number of factors. Some are inherent (cannot be changed easily) and others reflect management (Skjemstad, 2000; Dalal and Chan, 2001). The primary factors are:

- Temperature
- Rainfall
- Soil type
- Land use and management practices (including quantity and quality of inputs)

Changes in SOC levels depend upon the relative rates at which organic materials are added to and lost from the soil. In natural ecosystems, rainfall and temperature are the main factors determining plant biomass production and subsequent decomposition to SOC for a given soil type. These factors determine the equilibrium SOC level at a particular location. Equilibrium SOC levels are reached when additions of organic carbon equal the losses. Generally, the SOC level is highest in the surface layer and then declines with depth. However, distribution of SOC with depth tends to vary with different soil types. For instance, the decline of SOC with depth is relatively slow in black earths compared to krasnozems (Spain *et al.*, 1983). Furthermore, the vertical distribution of SOC varies with vegetation type. For example, the percentage of SOC in the top 20 cm (relative to the first metre) averaged 33%, 42% and 50% for shrublands, grasslands and forests respectively (Jobbagy and Jackson, 2000).

In agricultural systems (or other modified ecosystems), SOC turnover rates and equilibrium levels are further impacted by human activities, namely land use and management practices. These include practices that modify levels of carbon inputs as well as those that accelerate carbon losses.

Rainfall, temperature and soil types

Rainfall and temperature affect both inputs and losses of organic materials in soil ecosystems. As such, they control the boundaries for maximum carbon sequestration in soils in a given area (Australian Greenhouse Office, 2000). Rainfall plays an important role on SOC levels because of its effect on plant productivity. Dalal and Mayer (1986) reported an increase in organic carbon in virgin soils of 48 kg C/ha for each mm of rainfall. Temperature has a direct effect on the rate of decomposition of organic materials and SOC (Jenkinson, 1991). Thus the decomposition of SOC is more rapid in tropical regions than in more temperate regions (Dalal and Chan, 2001).

The equilibrium SOC level tends to vary amongst soil types. This is illustrated on a world scale by Table 4.2 (Eshwarn *et al*., 1993). On a per unit area basis, Histosols (not common in Australia) contain the highest mean SOC levels (205 t/ha) while Aridosols (very common in Australia) contain the lowest (4 t/ha). The correlation between SOC and soil types is partly due to zonal distribution of soil in the world in relation to climatic factors. For instance in Australia, Spain *et al*. (1983) reported the highest SOC levels in alpine humus soils and the lowest in desert loams in the 0-10 cm layer. By world standards, SOC levels in Australian soils are low. Chartre *et al.* (1992) estimated that 75 % of Australian soils have < 1 % SOC in their surface horizons.

Table 4.2 Organic carbon levels in soils (0-1 m) of the world (Source Eshwarn *et al*., 1993)

Soil order (US taxonomy	Australian Soil Classification	Area (km^2 x 10^3)	Organic carbon (Pg) (10^{15}g)	Organic carbon (t/ha)
Histosols	Organosols	1745	357	205
Andisols	-	2552	78	31
Spodosols	Podosols	4878	71	15
Oxisols	Ferrosols	11772	119	10
Vertisols	Vertosols	3287	19	6
Aridosols	Sodosols, Kandosols,Tenosols	31743	110	4
Ultosols	Sodosols, Kandosols, Kurosols	11330	105	9
Mollisols	Dermosols	5480	72	13
Alfisols	Sodosols, Kandosols, Chromosols	18283	127	7
Inceptisols	Calcarosols, Hydrosols	21580	352	16
Entosols	Rudosols, Podosols	14921	148	10
Misc. Land	-	7644	18	2
Total	**-**	**135215**	**1576**	**-**

Considerable variation exists in the SOC level within a specific soil type (Spain *et al*., 1983). Such variations in SOC levels are related to differences in management, climate, soil mineral composition, soil biota (vegetation and organisms), topography and the frequency of various catastrophic natural or human induced-induced events (fire, flooding, erosion) (Baldock and Skjemstad, 1999).

Soil types also affect SOC level through their composition (texture or particle size distribution of their mineral fraction). Soil texture influences the mineralisation of N pools (Chae and Tabatabai, 1986), and the net mineralisation of SOM and decomposition of plant material are more rapid in sandy soils than in clay soils. The lower net mineralisation of SOC in clay soils is linked to greater physical protection against microbial biomass attack (Hassink, 1992). Chan *et al*. (1998) reviewed SOC dynamics on lighter-textured soils (defined as the surface horizon <30-35% clay content). These are the major soils used for cereal cropping in Australia. The majority of these soils under cultivation have typical SOC levels approaching 1%. This was attributed to the low clay content and thus the lack of physical protection of the SOC.

Management practices

Soil organic carbon levels in virgin soils decline rapidly once cultivation (cropping) commences. This occurs because of the reduced carbon inputs into the soil system, and the increased decomposition of plant residues and SOC under cropping regimes. In Australia as well as in many other parts of the world, SOC levels found in the cropping soils are significantly lower than the corresponding soils found under natural vegetation. Globally, grassland and forest soils tend to lose 20 to 50 % of the original SOC content after 40-50 years of land use change (Bruce *et al*., 1999; Swift, 2001). In Australia, the loss of carbon varied from 10 to 60 % over 10-80 years of cultivation (Dalal and Chan, 2001). In Australia, 80 % of Australian soils are estimated to have lost up to 50 % of the total SOC in the top 20 cm of soil profile (Australian Greenhouse Office, 2000).

Several specific management practices have contributed to the loss of SOC observed under cropping. For example, Dalal and Mayer (1986) reported an increase in SOC of 48 kg carbon per ha per mm of rainfall in virgin soils, compared with only 29 kg carbon per ha per mm of rainfall in cultivated soils. Conventional cropping systems are characterised by burning of stubble and repeated tillage operations. Tillage not only increases soil aeration, but also increases the direct contact of soil microbes with crop residues and soil carbon materials, both leading to increased rates of decomposition (Skjemstad *et al*., 2001). The exact impact of tillage on SOC is dependent on the intensity and type of tillage operation as well as soil types (Chan and Pratley, 1998). Inappropriate or excessive tillage can lead to direct loss of SOC because of accelerated erosion. Soil degradation caused by these practices can also indirectly lead to SOC decline because of reduced crop yields (and thus reduced organic material input to the soil as crop residues). Similarly, stubble burning removes crop residues and thus promotes a decline in SOC levels.

4.4 Carbon Sequestration in Soils

Atmospheric concentrations of CO_2 and other GHGs can be decreased by either reducing their emission or by removing CO_2 from the atmosphere via photosynthesis and sequestering it in the different components of terrestrial and aquatic ecosystems (Fig 4.1). The removal of CO_2 from the atmosphere by increasing the soil carbon sink (sequestration of soil carbon) is one of the potential strategies for the second option. There are many agricultural management practices that can lead to carbon sequestration in the soil (Table 4.3).

Since changes in SOC reflect the a net balance of organic material additions and losses, effective agricultural practices that sequester carbon act by either increasing the amount of inputs and/or by reducing the amount of losses (Table 4.3). Subak (2000) collated data from a number of American studies on the likely magnitudes of rate of SOC sequestration for different management practice options (Table 4.4). The data emphasise the wide range of carbon accumulation possible under different management practices, with sequestration rates ranging 0.1-1.0 t C/ha/yr.

In North America, many investigations have evaluated the potential for carbon sequestration of conservation and zero tillage (Lal, 1997; Stockfisch *et al*., 1999; Uri and Bloodworth, 1999; Yang and Wander, 1999; Bergstrom *et al.,* 2001). Conservation tillage involves a significant reduction in the tillage intensity as well as retention of crop residues, both of which encourage increases in SOC (Table 4.3). The adoption of conservation tillage (including zero tillage) also reduces emission of greenhouse gases from farming systems because of reduced agricultural machinery use and fuel consumption.

Table 4.3 Agricultural management practices that can increase soil organic carbon level and the processes responsible for carbon sequestration

Management Practices	Processes /mechanisms in C sequestration	
	Increase inputs	Decrease losses
Cropping Land		
• Adoption of conservation/zero tillage	✔	✔
• Use of winter cover crops	✔	✔
• Improved crop nutrition	✔	
• Elimination of summer fallow		✔
• Use of forages in rotation	✔	
• Use of improved varieties	✔	
• Use of organic amendments	✔	
• Irrigation	✔	
Revegetation of Set- Aside Land		
• Re-establishment of perennial grasses	✔	
• Soil/water conservation measures (e.g. grassed waterways, shelterbelts)		✔
• Reversion to woodland	✔	
Pastureland		
• Improved grazing regime	✔	✔
• Fertiliser application	✔	
• Use of improved species/varieties	✔	
• Irrigation	✔	
Rangeland		
• Improved grazing regime	✔	✔
Degraded Land		
• Reversion to native vegetation	✔	
• Establishment of fast-growing crops	✔	✔
• Application of fertilisers	✔	
• Application of organic amendments	✔	
• Drainage/leaching of saline soils	✔	

Table 4.4 Estimated rates of carbon sequestration under different management practices from US investigations (Source: modified from Subak, 2000)

Actvity	Annual accumulation (t/C/ha/yr)	Scale
No-till compared with conventional till	0.14	Estimate for US Midwest corn production
	Not significant	
	0.14	Barley minimum tillage, USA, 1980s
	Quite variable, not as important as crop intensity (usually soil C increases related to till were below 20%; default of 10% increase)	Summary of field experiments (paired tillage plots) by a number of different investigators
	0.50	USA average
Crops	A:0.34 B:0.23	A: Projections based on 87 million hectares B: Projections based on 8.7 hectares in USA Midwest
	10-20% increase	IPCC default values
	0.20	Improved rotation on 51 million ha of land
Carbon inputs	0.33	Straw incorporation of 600 g $C/m^2/yr$ in Canada (increase in soil C of 650 g/m^2 over 20 yr
	0.18	Crop residue management
	Much greater influence than other factors	Cropping intensity (reduced fallows; higher C inputs by crop type)
	0.35	Sawdust and nitrogen (1,100 $g/m^2/31$ yr) (250 g C/m^2 additions; and 80 kg N ha as Ca $(NO3)_2$)
	0.20	Elimination of summer fallow on 9 million ha of land
Transformation	0.05-0.30	Agricultural land set-aside to perennial grasses in semi-arid to sub-humid regions of the Central USA
	0.75-1.0	Managed conversions to improved pastures
Other	0.10	Surface irrigation and water management
	0.1	Sub-irrigation on poorly drained soils
	0.1	Fertiliser management

Skjemstad (2000) considers that for agricultural management practices to be significant for carbon sequestration, soil carbon needs to be included. It has been estimated that up to 5 Pg of carbon can be sequestered in Australian soils over the next 20 years, with 75% of this likely to be through the soil via conservation tillage, residue management and adoption of improved cropping techniques

(Skjemstad, 2000). Because of the climatic conditions, carbon sequestration rates in Australia under these management practices are likely to be much lower than in North America.

In Australia, a review of SOC stored in the 0-10 cm soil layer in field trials (3- 19 years duration) on lighter-textured soils did not find consistently higher levels in soils under conservation tillage when compared to those under conventional tillage (most of the data points lie on or close to the 1:1 regression line shown in Fig. 4.3) (Chan *et al*., 1998). The ratio of carbon storage in soils under conservation and conventional tillage systems was positively related to the annual rainfall. As most of the wheat cropping in Australia is under rain-fed conditions in areas with annual rainfall of 250-600 mm, this suggests that the potential of using soil as a carbon sink by adopting conservation tillage practices alone to sequester carbon in the lower rainfall (<500 mm) areas of the Australian wheat belt is limited (Chan *et al.,* 1998).

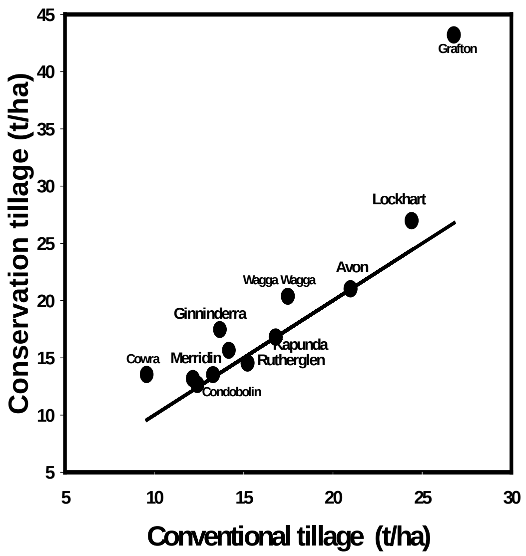


Figure 4.3 Soil carbon storage in 0-10 cm under conservation tillage and conventional tillage in Australia (Chan *et al*., 1998)

Under broad acre cropping in Australia, there is little evidence suggesting that SOC under conservation tillage has actually increased with time (Heenan *et al*., 1995). Results of a long- term tillage/stubble management/rotation experiment on a red earth (kandosol) in Wagga Wagga (annual rainfall of 570 mm), NSW showed that under continuous wheat-lupin rotation, SOC declined continuously with time over 14 years period under all tillage and stubble management practices. The highest rate of carbon loss (0.4 t C/ha/yr) was found with continuous wheat cropping under conventional tillage (three cultivations per year) and stubble burning. Near equilibrium level of SOC was achieved only under no-tillage and stubble retention in a 1:1 year pasture-wheat rotation. Sequestration of SOC is expected to be slow under the semi-arid environment due to low biomass productivity and high decomposition rates because of high temperatures (Chan *et al*., 2001b).

Many of the other management practices listed in Tables 4.3 and 4.4 act by increasing carbon input to the system. This can be achieved in three ways:

- Intensification by increasing the duration of photosynthetic activity by, for example, the use of pasture phase and cover crops.
- Increasing yield with the use fertilisers, better plant varieties and irrigation.
- Direct organic amendments with farmyard manure and RO products.

Increased carbon inputs as crop biomass are well documented to increase SOC linearly (Rasmussen and Albrecht, 1998; Halvorson *et al.*, 1999). Soil Organic carbon increases under pasture in the low rainfall areas are small because of low yield. In the semi-arid areas of New South Wales, Chan *et al.*, (2001) found that SOC increased significantly only in the top 2.5 cm of a kandosol after four years of pasture phase. Higher SOC levels found under lucerne compared to other pasture species was due to the higher dry matter yield of lucerne. Thus, amendment with RO on cropping systems in Australia represents an attractive option to increase carbon inputs.

Returning organic materials to farmland is a time-honoured practice worldwide and is the key to many sustainable agricultural systems found even today. The ability of farmyard manure (FYM) addition to increase SOC level is well illustrated by the classic Rothamsted long-term experiment. With annual additions of 35 t/ha of FYM (equivalent to 3 t C/ha/yr) since 1852, SOC storage in the topsoil has increased threefold and is still increasing (Fig.4.4). Particularly interesting is the treatment where FYM was applied from 1852 to 1871 and then discontinued. There was a subsequent decline in SOC, but the level is still significantly higher than the unmanured control >100 years after termination of the FYM treatment.

The potential for soil carbon sequestration by a given soil is dependent on its current soil carbon level. A degraded soil with low SOC will have a greater potential to sequester carbon than a soil that has been under optimum management for a number of years (Lal, 1997; Felton *et al*., 2000; Subak, 2000). Returning degraded cropping land to perennial vegetation (pasture or trees) can substantially increase the rate of carbon sequestration (0.3-0.5 t C/ha/yr) (Potter *et al.* 1999; Post and Kwon, 2000). Lal (1997) estimated that the global carbon sequestration rate from restoring degraded land is 3.0 Pg/yr which is 24 times the sequestration achievable via adoption of conservation tillage (0.125 Pg/yr). By contrast, poorly managed degraded land acts as a source of carbon (Ash et al., 1995).

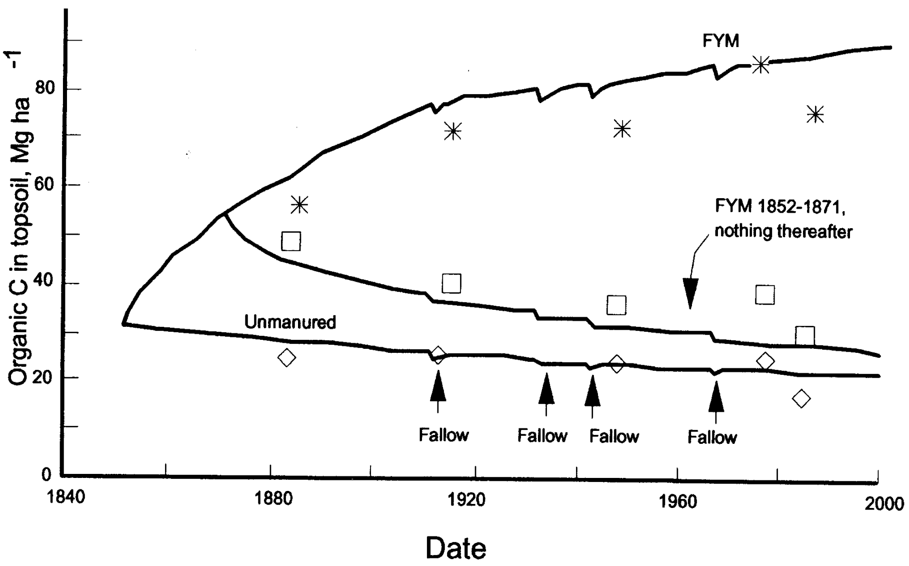


Figure 4.4 SOC in the topsoil of long-term experiment at Rothamsted, England (the symbols show experimental results; solid lines are a model fit) (Source: Jenkinson, 1991)

Smith *et al*. (2000a) reviewed the SOC sequestration potential of different land management practices in Europe and concluded that any single land-management change in isolation is unlikely to mitigate all of the carbon needed to meet Europe's climate change commitments. Integrated land management strategies shows considerable potential for mitigation. The strategies considered included conservation farming, conversion of intensive cropping to less intensive (eg ley/crop rotations), natural woodland regeneration, bioenergy crop production, and the application of animal manures, biosolids and cereal straw.

4.5 Carbon Sequestration Potential of NSW Soils

Soils cannot accrue carbon indefinitely. As discussed in Section 4.3, the SOC of a particular soil type if left undisturbed, will eventually reach an equilibrium value under a given set of climatic conditions (mainly temperature and rainfall). The carbon sequestration potential of soil at a particular site can be estimated as the difference between the current SOC level and this equilibrium level determined on adjacent virgin sites (Bruce *et al*., 1999). However, the soil carbon data for NSW soils is incomplete for the following reasons:

- existing SOC data were obtained by different methods of determination and based on different sampling depths
- The bulk density data of the soil layer, required for estimation of carbon storage on an area basis, are often not available
- Most data were obtained on cultivated soils. SOC levels of virgin soils have rarely been measured

The Australian Greenhouse Office (Australian Greenhouse Office, 2000) has highlighted the paucity of information on SOC in Australia as a potential problem in the inclusion of agricultural management activities as an additional sink activity under Article 3.4 of the Kyoto Protocol.

In view of the these limitations, we have estimated the carbon sequestration potential for NSW soils in two ways:

Paired sites comparison

From the available field soil carbon data, the carbon sequestration potential was calculated from the difference in SOC levels of 0-10 cm layer for a number of paired sites of cropped and adjacent "undisturbed" areas. In the absence of bulk density information, a bulk density value of 1.3 Mg m^{-3} was assumed. These estimates for different soil types at a number of locations throughout NSW are given in Table 4.5.

Modelling approach

Assuming 1 % as the SOC levels for cropping soils, the CENTURY model (Metherell *et al.*, 1993) was used to predict equilibrium SOC levels for soils with three soil texture classes (sand, loam and clay) in three different locations in NSW. Details of input data and assumptions used in the modelling are provided in Table A6 (Appendix) and the results of the modelling are given in Table 4.6.

Table 4.5 Soil organic carbon levels of NSW soils - paired sites : cropping vs undisturbed areas

		Non-cropping		Cropping							
Location	**Soil type**	**OC%**	**OC, t/ha**	**OC%**	**OC, t/ha**	**Loss* in OC, t/ha**	**Comment**	**Rainfall (mm)**	**Temp (^{O} C)**	**% Clay**	**Reference**
Somersby	Yellow earth (kandosol)	1.84	23.92	1.18	15.34	8.58	CT** vs native bush	1300	16.2-25.6	15	Wells et al. (2000)
Wagga Wagga	Red earth (kandosol)	1.81	23.53	1.35	17.55	5.98	CT vs permanent fence line	570	9.0-21.8	27	Chan and Mullins (1994)
Cowra	Red duplex (chromosol)	2.91	37.83	0.89	11.57	26.26	CT vs >20 permanent Pasture	612	7.8-23.7	13	Chan and Mullins (1994)
Wellington	Red brown earth/earth	3.64	47.32	0.56	7.28	40.04	CT vs woodlands	620	10.3-22.7	11/42	Geeves et al. (1995)
Walgett	Vertisols (vertosols)	1.2	15.6	0.75	9.75	5.85	CT vs natural Mitchell grass	480	12.7-27.2	61	Chan (1989)
Parkes	Earth (dermosol)	2.85	37.05	1.51	19.63	17.42	CT vs native pasture	579	11.3-22.9	24	Geeves et al. (1995)
Nyngan	Red earth (kandosol)	2.14	27.82	0.79	10.27	17.55	CT vs woodland	431	11.8-25.7	32	Chan et al. (2001a)
Mean	-	2.34	30.5	1.00	13.1	17.4					

* calculated based on 0-10 cm layer and assuming bulk density of 1.3 Mg m^{-3}
** CT = conventional tillage

Table 4.6 Equilibrium soil organic carbon levels predicted using CENTURY for different soil types at three different locations in NSW

LOCATIONS	Sand (e.g.Yellow earth)			Loam (e.g. Red Brown Earth)			Clay (e.g. Vertisols)		
	OC levels, (%)	OC pool (t/ ha)	Additional OC sink (t/ ha)*	OC levels (%)	OC pool (t/ ha)	Additional OC sink (t/ ha)*	OC levels (%)	OC pool (t /ha)	Additional OC sink (t /ha)*
Sydney	1.71	22.21	9.21	2.35	30.61	17.61	4.05	52.71	39.71
Cowra	2.05	26.64	13.64	2.63	34.22	21.22	3.80	49.34	36.34
Wagga	1.95	25.35	12.35	2.46	32.04	19.04	3.50	45.52	32.52

* Difference between predicted equilibrium pool and existing pool under cropping, assuming concentration of 1 % ie. existing pool of 13 t ha^{-1}

The paired-sites carbon data indicate that on average, the cropping soils have lost 57 % of their total SOC. This compares well with other Australian data (Dalal and Chan, 2001). Losses of carbon in the cropping soils compared to adjacent "undisturbed" areas, taken as a measure of carbon sequestration potential, range from 5.85 to 40.04 t ha^{-1}. The greatest loss was found in a Red Brown Earth (with a loamy surface soil) at Wellington and the smallest loss was found in a Vertisol (a clay) near Walgett (Table 4.5). Clear relationships between carbon loss, soil type and climate are not apparent. This could be due to the limited data set and uncertainty of the extent to which the SOC levels detected in the "undisturbed" areas actually represent the "equilibrium" SOC levels. Most of the chosen "undisturbed" areas - permanent fence lines, pastures, etc have been disturbed to varying extents. However, it is notable that the average SOC of the cropping soils was 1.0 % (Table 4.5).

For the modelling, the equilibrium SOC levels were predicted by running the model for the equivalence of 2000 years under permanent pasture. Carbon sequestration potential was estimated as the additional carbon sink between that of the equilibrium and the existing storage found in the cropping soils (assumed to be 13 t/ha to 10 cm depth, for SOC level of 1%).

Results indicate the predicted equilibrium SOC level increase with clay content (highest in the clay soil). As shown in Fig.4.5, the additional carbon storage is largely in the more resistant forms of SOC, particularly those in the passive pool. The mean carbon sequestration potential ranges from 11.7 t/ha for sandy soil, 19.3 t/ha for loams and 36.2 t/ha for clay soil (Table 4.6).

Therefore results from both experimental and modelling approaches indicate large carbon sequestration potential of cropping soils in NSW. The amounts of carbon that can be sequestered tend to be higher for the clay soils than the sandy soils and range from 6 to 40 t/ha. For the loamy soil, it is about 20 t/ha. With the most conservative estimate of 6 t/ha, the 907,000 ha of cultivated land in the Central West of NSW (Table 2.1) have the potential to sequester a total of almost 5.5 million tonnes (5.5 Tg) of carbon. This is a relatively modest contribution to carbon sequestration in the total accounting process, given that the mineralisation of SOC in Australia contributes 4 Tg of carbon every year to greenhouse gases (Swift, 2001). However, if it is assumed that RO contains 20% carbon, that only 10% of the carbon applied as RO is retained as SOC (see Fig. 4.2) and that 50% of the land is available for RO application, this represents a potential market for 137.5 million tonnes of RO. This estimate is restrained by the assumptions made in its calculation. However, it is clear that the potential capacity of cultivated land as a market for RO far exceeds the supply capacity of the RO industry in the Sydney Basin.

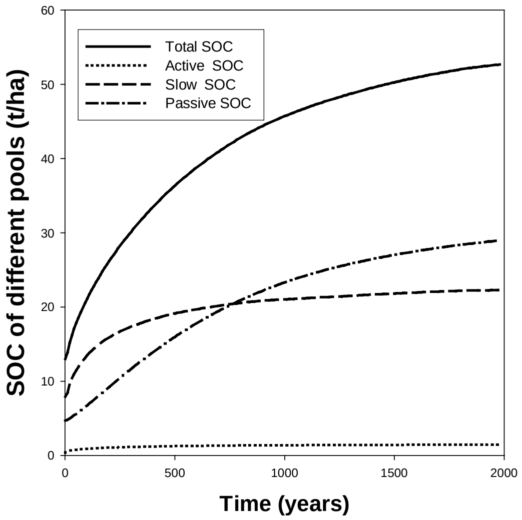


Figure 4.5 Equilibrium SOC levels in the different pools of a clay soil at Sydney as predicted using the CENTURY Model

Both the Australian Greenhouse Office (AGO) and the Cooperative Research Centre (CRC) for Greenhouse Accounting are examining modelling approaches for carbon accounting in Australia, but published reports are more focussed on land use changes in forest ecosystems (Paul *et al*., 2002). The approach for soil carbon accounting by the AGO is to estimate changes by the RothC soil carbon model and to use paired site data to confirm the model and confirm predictions (Webbnet Land Resources Services Ltd, 1999). Additional paired site data is now being gathered from newly cleared areas in NSW, Queensland and Western Australia. Current activities in NSW are limited to one area in western NSW (Brian Murphy, pers. comm.) though up to a total of 10 sites is planned (Webbnet Land Resources Services Ltd, 1999).

DLWC was also commissioned in 2002 by the Australian Greenhouse Office to produce a soil organic carbon map of NSW (R. Banks, DLWC, pers comm.). The map (1:100,000 scale) is based on existing information on soil organic carbon levels of NSW soils under natural vegetation and does not include agricultural soils. Reliability of the map is variable depending on the amount of existing information on soil organic carbon for different regions. For soils within the target area for RO (Section 2.2) the reliability of the map is poor, reflecting the lack of available information on soil organic carbon in soil survey reports carried out in the past.

Accounting and trading systems

5.1 The Kyoto Protocol: carbon sinks, carbon credits and emissions trading

In recognition of the adverse effects of unregulated GHG emissions on global climate, in Rio de Janeiro in 1992 the United Nations adopted a Framework Convention of Climate Change (UNFCCC) to develop mechanisms to stabilise atmospheric GHG concentrations. Subsequent meetings of the parties to the UNFCCC at Kyoto in 1997 drafted a protocol (the Kyoto Protocol) to place binding GHG emission targets (Annex B of the Protocol) on signatory nations. The targets are expressed as a percentage of the defined base year of 1990 and are to be met by the year 2010, with a measurement period of between 2008 and 2012. As a signatory to the Kyoto Protocol, Australia is required to introduce policies and measures to restrict the growth of GHG emissions to 8% above 1990 levels and to provide an annual inventory of GHG emissions since 1990. Constraining the increase in emissions to meet the Australian target is equivalent to a reduction of ~ 20 % from the current annual growth rate of emissions or an equivalent reduction of ~80 Mt of CO_2 per year (Jackson, 1998).

An important feature of the Kyoto protocol is that emission targets can be met directly by decreasing GHG emission rates and indirectly by increasing the rate at which they are removed from the atmosphere (ie increasing carbon sinks by carbon sequestration). Thus emissions by a signatory country can be offset by increased carbon sequestration, provided that the net effect is ‘real and additional’. The protocol also has established three market-based instruments (Kyoto Mechanisms) that allow countries to buy or earn credits to facilitate cost-effective reductions in greenhouse gas emissions (Australian Greenhouse Office, 2000). The Kyoto Mechanisms are:

1. the Clean Development Mechanism, a means to earn credits by investing in emission reduction projects in developing countries,
2. Joint Implementation, a means to earn credits by investing in emission reduction projects in other Kyoto-signatory countries, and
3. International Emissions Trading, in which industrialised countries can buy and sell emission (or carbon) credits amongst themselves.

Emissions trading enables developed countries that are unable to meet their emission targets, to offset their carbon emissions by the purchase of carbon credits from other participating countries that have reduced their net emissions (decrease in emissions plus increase in sequestration) beyond agreed targets. The carbon credits are sold as certificates that are linked to the technical information required supporting the claim for a reduction in net carbon emission (Holloway, 1998).

The original agreement at Kyoto recognised soil as a significant terrestrial storage for carbon (Article 3.3), but limited the activities eligible for carbon accounting purposes to afforestation and reforestation. In 2001, the UNFCCC meeting at Bonn included land management systems as allowable terrestrial carbon sinks (Article 3.4). Thus, there are now opportunities for the inclusion of increases in soil carbon sequestration under improved pasture and cropping management systems to be incorporated into the articles of the Kyoto Protocol. Significantly, Australia is yet to ratify the Kyoto Protocol and to implement a national emission trading system.

5.2 Soil carbon accounting - issues and challenges for recycled organics use in agriculture

Although soil constitutes the largest terrestrial storage pool for carbon (Fig 4.1), only changes in the carbon fluxes between the soil and the atmosphere that lead to an increase in soil carbon are eligible for carbon accounting. Carbon fluxes from the soil include CO_2 emissions from the decomposition of plant residues and root detritus, and from the respiration of living plant roots and microorganisms (Rosenzweig and Hillel, 2000). They also include the physical loss of insoluble or soluble carbon through erosion or leaching (Rosenzweig and Hillel, 2000).

There are a number of key features in carbon accounting systems that need to be demonstrated under the conditions of the Protocol (IPCC, 2002). The system must be:

- *transparent*, with assumptions and methods clearly explained so that information can be traced to the underlying data
- *consistent* with the scientific principles of carbon processes over space, pools and time
- *comparable* across different data sets and over time. This might require the development of standardisation in data collection and measurement
- *complete*, so that all applicable sources and sinks are included in the accounting process
- *accurate*, with unbiased data that has an acceptable level of precision

- *verifiable* by a third party, based on substantiated data, models and methods.

Thus among the challenges for land management systems and the use of RO in land management systems to sequester soil carbon, is to verify that carbon is actually being sequestered and maintained in the long term (Rosenzweig and Hillel, 2000; Izaurralde, *et al*., 2001). This will be discussed in more detail below, but in Australia the AGO has established a National Carbon Accounting System to provide data on carbon sinks. The verification of carbon sequestration over the long term might also be in an environment with increasing atmospheric CO_2 and warmer mean global temperatures. Each of these factors complicates the estimation of sequestered carbon attributable to improved land management. For example, plants grown in increased atmospheric CO_2 concentrations exhibit 'CO_2 fertilisation' responses (Schlesinger and Andrews, 2000), that increase above and below ground biomass. In contrast, increased temperatures increase soil carbon fluxes by promoting soil microbial and plant root respiration (Schlesinger and Andrews, 2000).

The Kyoto Protocol allows two accounting approaches to determine changes in carbon stocks (IPCC, 2002). In land based accounting, net carbon stock changes on land units subject to Kyoto activities are determined for the commitment period. In activity based accounting, the carbon stock changes attributable to given activities are determined per unit area and multiplied by the total area on which the activities occur. Either approach or various combinations of them can be adopted by Kyoto signatory nations provided double accounting is avoided.

The potential for composted RO products to sequester SOC in Australia was discussed in Section 4, which emphasised the limitations imposed by soil texture and climatic conditions. The potential for sequestration would be enhanced if RO use were integrated with improved land management practices such as minimum tillage and crop rotation to maximise organic matter inputs to the system, and to minimise the disturbances of cultivation and soil erosion.

Several issues need to be clarified and resolved before RO use in agricultural production would qualify as a carbon sink within a carbon accounting system. Many of these issues are also relevant to land management systems in general and include (1) soil carbon inventory data, (2) the permanency of sequestered soil carbon, (3) the need for full accounting, and (4) trading processes:

1. The accounting process under the Kyoto Protocol requires that the effects of land use changes are determined on soil carbon stocks: a) existing under pre-cleared conditions up

to and including 1990 (the soil carbon flux baseline year), measured during 1990, and b) over the 2008-2012 accounting period and future accounting periods yet to be determined. Existing soil carbon data from research in NSW farming systems are in the context of land sustainability issues rather than of carbon accounting and are not complete (Felton *et al*., 2000). Current activities commissioned by the AGO to estimate and map soil carbon stocks are in progress (Webb, 2002). These have accessed national soil databases established for other purposes but highlight their deficiencies and the need for improved information. Deficiencies identified included the general lack of bulk density measurements, and the lack of data below 10 cm depth or from virgin sites. Significant sets of data were estimates or default values. The reliability of carbon maps is variable and is poor for the soils within the target area for RO (Section 2.2) (R. Banks, DLWC, pers comm.).

Felton *et al*. (2000) also point out these deficiencies in much of the current estimates for total soil carbon. They also highlight variations in the treatment of soil samples prior to measurement and in the analytical methods used, and errors inherent in the wet chemical analytical methods used in the past. These factors make data comparisons difficult. Soil sampling procedures must account for spatial and temporal variability (Bruce *et al.*, 1999) and estimates are best made on a scale that is representative of farm units with consideration of topography (Bergstrom *et al*., 2001). The Australian Greenhouse Office has considered many of these issues in its recent development of soil sampling protocols and analyses for soil carbon estimates (McKenzie *et al*., 2000) and of soil carbon conversion factors for existing data (Skjemstad *et al*., 2000).

Other factors that need consideration are that current methods to measure soil carbon stocks directly are costly, time consuming and of insufficient sensitivity to distinguish small, short term changes in carbon sequestration against much larger existing soil stocks (Izaurralde *et al*., 2001). Developments in these procedures are essential. They include the application of high-resolution remote sensing, continuous direct measurements of small soil carbon fluxes against a background of relatively high soil carbon, and improved simulation modelling.

These deficiencies mean that existing soil carbon measurements in Australia require manipulation before being acceptable for national carbon accounting purposes and further validation and data collection are necessary. Smith (2000a) drew essentially the same conclusions in an assessment of soil carbon sequestration in Europe. Agreement is also needed on which control or baseline soil carbon levels are used to assess sequestration.

Izaurralde et al. (2001) discusses this in some detail. Controls based on carbon levels in soils at the beginning of the measurement period prior to treatment are one option. However, these will in many cases give different answers to controls based on carbon levels determined at the end of the measurement period in an adjacent field under conventional practice. Whatever controls are used, it would be important to ensure that both soil carbon gains and avoided carbon losses are included in the assessment.

2. Improved crop and soil management systems are the key to ensure that that SOC derived from RO products are stabilised and represent a permanent sequestration. Thus systems must be able to demonstrate that soil carbon accessions by the return of crop residues or by RO additions are maintained by practices that minimise the rate of soil carbon decomposition. These were discussed in Section 4. The effectiveness of all management practices aimed to restore and conserve soil carbon to a new equilibrium level is constrained by the limitations of soil texture and climate. These are the primary determinants for equilibrium soil carbon levels (Section 4).

   Research from the United States has demonstrated the potential for conservation farming practices to reverse the soil carbon losses associated with cultivation-based farming practices (Swift, 2001). However, each disturbance or change in crop residue input requires a period of constant management for a new equilibrium to be reached. Many of the gains in soil carbon and organic matter from conservation farming practices can be lost by inappropriate cultivation and permanence will only be guaranteed if there are long term changes in behaviour and attitudes (Pretty and Ball, 2000).

   The challenge for carbon sequestration in Australia's cropping soils is the variable climate (Swift, 2001). Thus, in conservation farming systems, the remaining carbon in decomposed crop residues retained in the soil is often less than required to offset the soil carbon losses. This is illustrated in NSW by the continued decline in soil carbon since the introduction of minimum tillage and other conservation farming practices (Chan *et al*., 1998; Felton *et al*., 2000; Dalal and Chan, 2001). It also provides an opportunity to use RO products as an additional input of stabilised carbon and more effective fertiliser regimes to increase crop biomass as part of improved management systems for cropping soils. Recent studies over 10 years in North America conclude that fertiliser application in conservation farming systems is the determinant for the increased SOC found (Campbell *et al*., 2001).

Simulation models such as CENTURY (see Section 4) or more recent ones such as CQESTR (Rickman *et al*., 2001) to predict changes in soil carbon have been useful to provide guidance on what management practices offer the most potential for a given soil in a particular climatic zone (Izaurralde *et al*., 2001; Smith *et al*., 2001). However, these models are only as good as the assumptions they use for soil carbon dynamics and dependence upon climatic conditions, and the accuracy of the input data for soil carbon. None of the models presently include additions of stabilised organic carbon as composted products.

3. An accounting process for soil carbon must include a total carbon account to reflect the 'whole-of-life' costs and benefits attributable to a demonstrated increase in soil carbon. For instance, for RO use the carbon account must include:
   - increased sequestered soil carbon derived from the RO products applied (direct sequestration) and from increased production of biomass resulting from RO application (indirect sequestration),
   - the carbon cost of fossil fuel consumption involved in the manufacture, transport and application of RO products (direct carbon losses), and
   - the carbon savings due to reduced fossil fuel consumption involved in reduced tillage, reduced use of nitrogenous fertilisers and pumping costs for irrigation water, or from reduced carbon loss due to erosion and leaching (avoided carbon losses).

Despite this, recent estimates of the potential for carbon gains in North American soils, equivalent to up to 15% of the total annual carbon mitigation targets for the United States and Canada, have ignored direct and avoided carbon losses (Bruce *et al*., 1999).

The concepts are complex and are still evolving. Importantly, only the anthropogenic (human-generated) sources of GHG from improved management practices would be included in the Kyoto accounting process. Biogenic (natural) sources such as the CO_2 generated by organic matter decomposition during the composting process, are not accountable (ROU, 2001). The accounting process should recognise potential reductions in nitrogen fertiliser use on RO treated soils because of the fertiliser value of RO and improvement in soil nutrient retention and cycling. It must also recognise the potential for increased use of nitrogen fertiliser as part of an integrated approach to increase plant productivity, crop residue deposition and SOC (Campbell *et al*., 2001). Nitrogen fertiliser is a potent source of CO_2 during its manufacture and of nitrogen oxides in its use in agriculture (Smith, 1999; Schlesinger, 2000).

The needs for total carbon accounting can be summarised in the following equation:

Soil Carbon sequestered	=	*Direct Sequestration*	+	*Indirect Sequestration*	-	*Direct Carbon Losses*	+	*Avoided Carbon Losses*

Direct carbon losses and avoided carbon losses can be calculated. They represent some of the hidden energy costs and savings in the equation. In a number of papers over recent years, Schlesinger has discussed the hidden energy (and thus GHG emission) costs of practices such as nitrogenous fertilisation and irrigation proposed to increase soil carbon sequestration (Schlesinger, 1999; Schlesinger, 2000). With the hidden costs considered, Schlesinger (2000) concludes that carbon sinks for soils would only occur in abandoned agricultural land returned to native vegetation and discounts the value of manures to increase net soil carbon sequestration. Smith (1999) and Smith (2000a) are more positive and cite a substantial reversal of trends in carbon decline in agricultural soils with conservation practices. However, Smith (1999) also emphasises the need to better understand GHG sources and sinks and to develop better soil management practices.

Adequate data to determine direct and indirect sequestration are not available in Australia and the baseline carbon data that is available might not be acceptable for accounting purposes (Felton *et al*., 2000; Smith, 2000). These issues were discussed above. They emphasise the need to fill the data gaps in soil carbon and to refine the methods to verify soil carbon sequestration on an annual basis (Izaurralde *et al*., 2001), as is required by Kyoto carbon accounting processes. The calculations necessary to determine changes in soil carbon is complex and need to include inputs for differential decomposition rates of organic matter pools from RO and crop residues (Campbell *et al*., 2001).

Other factors that need consideration include any indirect impacts that a carbon-sequestering activity has on carbon storage in another location or time frame (‘leakage’` effects). For example, removal of land from crop cultivation might lead to increased cultivation in other areas to meet demand for produce. This occurred after logging bans in Thailand in 1989, which encouraged increased logging in neighbouring countries (IPCC, 2002).

4. If established as a trading market, sequestered soil carbon offers an annual cash flow for farmers by direct payments from emitters to sequester and provides an incentive for farmers to use RO. In Australia, a market in carbon has emerged in the forestry industry

at $15 per tonne (Holloway, 1998). A model has been developed as a decision support system for forestry based on carbon trading (Hassall & Associates, 2001). Although market forces would ultimately determine the value of carbon credits in trading systems, there are several mechanisms by which it could be calculated (Pretty and Ball, 2000):

- calculate the external costs of each tonne of carbon emitted to the atmosphere by assessing damage, mitigation and adaptation costs. These have been calculated in Europe to be US$95 per tonne of carbon, which represents the upper limit of what could be paid in trading systems
- calculate the cost of implementing projects that would deliver the emission reduction target
- assess what business are currently willing to pay others as an offset for their own carbon emissions. Companies would be in effect, hedging against the risk of future enforced payments to meet tougher carbon emission regulations.

A number of carbon exchange or trading systems have recently been established internationally, in which carbon credit values are being set at much lower levels than the theoretical US$95 per tonne of carbon (Pretty and Ball, 2000):

- The consortium GEMCo (a group of Canadian utility and energy companies) has agreed to pay via an insurance firm $1-$3 per tonne CO_2 ($3.67-$11 per tonne carbon, or $14.80-$24.80 per ha) to Iowa farmers for up to 3.8 million tonnes of carbon emission reduction credits.
- An internal trading system set up by seven North American companies to cut emissions by 20 % below 1990 levels has established the value of carbon credits at $5-$16 per tonne carbon.
- BP Amoco uses carbon credits of $22 per tonne carbon in its trading system to reduce the company's accountable CO_2 emission
- The Tokyo Electric Power Company has invested US$5 million in Tamar Tree Farms in Tasmania for 3000 ha of eucalyptus plantation. This is expected to yield 13,0000 tonnes of carbon credits at $38 per tonne carbon.
- The Dallas-based utility company, Central and South West Corporation has spent US$5.4 million on acquiring 7,000 ha of rangeland. Based on the potential to sequester one million tonnes of carbon the credits are estimated at $5.40 per tonne carbon.

These trading systems demonstrate the range of values placed on carbon credits and point to difficulties in estimating the benefit to farmers if a trading system were to be established for sequestered soil carbon. In Australia no decisions have yet been made on the inclusion of soil carbon sequestration in the National Carbon Accounting System (Jennifer Brett, AGO, pers. comm.) but accurate simulation modelling for soil carbon sequestration will play a significant role. An important question for farmers is how much area of land is required to make carbon trading viable. Within the forestry industry Holloway (1998) suggests that while individual growers may not have the land available to dedicate to carbon trading, several growers from one district could combine for trading purposes to make the project viable.

A significant challenge for a carbon trading system based on soil carbon sequestration is the Kyoto Protocol requirement that carbon is accounted for and traded on an annual basis. Thus, improved management practices that involve RO and propose to sequester soil carbon must demonstrate annual changes in soil carbon stocks. This is complicated by a number of factors. These include the long-term nature of soil carbon sequestration, the sensitivity of soil carbon to disturbance, the variability of the Australian climate and the sensitivity of existing methods to measure changes in soil carbon stocks.

The AGO has developed procedures necessary for carbon accounting and trading for vegetation-based carbon sinks (Francis, 1999). Accounting and trading for soil-based carbon sinks would most likely involve similar procedures. They are:

- Develop an inventory of emissions and sequestration
- Develop an action plan to minimise net emissions
- Forecast expected reductions in emissions
- Sign a Greenhouse Challenge agreement with the Commonwealth
- Monitor progress and providing regular reports to the Commonwealth and the broader Australian community
- Agree to random independent verification

The procedures are in a workbook which provides information on establishing a baseline emissions scenario, deciding which carbon pools to measure and how often, and estimating carbon sequestration in the years between measurements. As discussed previously, carbon accounting in soil sinks provides greater challenges in these respects than sinks based on forestry. Several issues need resolution before soil carbon sequestration would be acceptable in Australia’s National Carbon Accounting System.

5.3 Other credit trading schemes - salinity credits and water credits

Similar to the carbon credit schemes, as part of the market-based solutions for environmental problems, such as salinity and loss of biodiversity, there are other trading schemes being contemplated by different government agencies. There is a recognition that a market-based approach supported by the community is one of the key sustainable long term solutions to salinity (NSW Department of Land and Water Conservation, 2000)

Conceptually, a salinity credit scheme can be set up to address salinity problem based on management targets for the landscape, such as reducing groundwater recharge. The latter has been identified as the cause of salinity problems in many parts of Australia. People would gain credits when they managed their land in a way that decreased the amount of recharge, for example through investing in planting trees or undertaking revegetation. Business, council or land managers who were seeking to manage their land in a way that increased salinity could be required to buy credits to offset the impact of their actions. Similarly, irrigation rights can be traded under a water credit scheme.

For the successful implementation of any trading schemes, the product, which is to be traded will need to be accurately defined. In the case of salinity credit, research is needed to quantify the impacts of vegetation, including tree planting on salinity control in different landscapes. Much of this research is still to be carried out.

Moreover, unlike a carbon credits trading scheme in which RO because of its carbon content has a direct sequestration value, the possible benefits of RO in other trading schemes (salinity credits, water credits) are likely to be indirect only. For instance in the case of salinity control by tree planting, application of RO might improve the establishment and growth of trees under a saline environment and therefore help to achieve the management target of reducing groundwater recharge in a shorter time. However, the mechanism for gaining salinity credit under such circumstances would be very complex and is not clear.

Recommendations

A key conclusion from this review has been that agricultural soils in NSW have the potential to sequester carbon derived from RO. However, there is insufficient existing data or knowledge about soil carbon levels in NSW to validate the effectiveness of existing or improved soil management systems to sequester RO-derived soil carbon under local climatic conditions. Recommendations from this are that:

- Studies are required to identify gaps in existing soil baseline data for organic carbon in targeted NSW soils based on soil texture, climatic zone and management practices. This is necessary to generate data to fill in the gaps on existing and potential soil carbon levels within the target area for RO (within a 200-250 km radius of Sydney) and identify soils, management practices and locations with the most potential to sequester RO-derived soil organic carbon. Current activities of the Australian Greenhouse Office in generating soil carbon data are in recently cleared areas and do not consider the potential for RO. However, they would complement any soil-testing program with a RO-focus.

- Research in targeted areas is necessary to develop and validate effective soil carbon management practices to sequester carbon from RO products applied to in selected soil types, and to provide the data necessary to develop modified models for soil carbon dynamics that include carbon inputs from RO. Part of this process would be to develop specific product specifications for RO products intended to promote carbon sequestration and ensure consistency of product. Some quality parameters relevant to the capacity of RO products to promote soil carbon sequestration include carbon content and organic matter maturity, moisture content, and available nutrient status.

Another key finding was that although some carbon trading schemes exists in Australia and land management practices to increase soil carbon sequestration is now eligible for carbon accounting purposes, Australia has yet to reach decisions on its inclusion in the National Carbon Accounting System. Thus:

Resource NSW and other key stakeholders in the recycled organics industry should engage the Australian Greenhouse Office in discussions on its position for the inclusion of soil carbon sequestration in the National Carbon Accounting System and possible mechanisms for a soil carbon trading system.

References

ABS 1998. Agriculture, New South Wales 1996-97. In: ‘Agricultural Statistics – General’. Australian Bureau of Statistics.

Anonymous 1993. Utilization of municipal solid waste compost: research trials at the Johnson City, Tennessee facility. *Compost Science and Utilization* 1: 42-48.

Anonymous 2000. Composting reduces fuel and labour costs on family farms. *BioCycle* 41: 72-73.

Albiach, R., Canet, R., Pomares, F. and Ingelmo, F. 2000. Microbial biomass content and enzymatic activities after the application of organic amendments to a horticultural soil. *Bioresource Technology* 75, no. 1: 43-48.

Albiach, R., Canet, R., Pomares, F. and Ingelmo, F. 2001. Organic matter components and aggregate stability after the application of different amendments to a horticultural soil. *Bioresource Technology* 76: 125-129.

Australian Greenhouse Office 2000. Greenhouse Sinks and the Kyoto Protocol - An Issues Paper. Australian Greenhouse Office, Commonwealth of Australia.

Avnimelech, Y. and Cohen, A. 1988. On the use of organic manures for amendment of compacted clay soils: effects of aerobic and anaerobic conditions. *Biological Wastes* 26: 331-39.

Baldock, J.A. and Skjemstad, J.O. 1999. Soil organic carbon/soil organic matter. In: ‘Soil Analysis: An Interpretation Manual’. CSIRO Publishing, Victoria, Australia. Eds. K.I. Peverill, L.A. Sparrow and D.J. Reuter, pp. 159-170.

Bergstrom, D. W., Monreal, C. M. and Jacques, E. 2001. Influence of tillage practice on carbon sequestration is scale-dependent. *Canadian Journal of Soil Science* 81:63-70.

Bernal, M.P., Navarro, A.F., Sanchez-Monedero, M.A, Roig, A. and Cegarra, J. 1988. Influence of sewage sludge compost stability and maturity on carbon and nitrogen mineralisation in soil. *Soil Biology and Biochemistry* 30: 305-313.

Bevacqua, R. F. and Mellano, V. J. 1993. Sewage sludge compost's cumulative effects on crop growth and soil properties. *Compost Science and Utilization* 1: 34-37.

Bishop, A.L., Powell, K.S., Gibson, T.S., Barchia, I.M. and Wong, P.T.W. 2002. Mortality of grape phylloxera in composting organics. *Australian Journal of Grape and Wine Research* 8: 48-55.

Blair, G. J., Lefroy, R. D. B. and Lisle, L. 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research* 46: 1459-1466.

Block, D. 1997. Disease Suppression On the Links. *BioCycle* 38: 62-65.

Bruce, J. P., Frome, M., Haites, E., Janzen, H., Lal, R. and Paustian, K. 1999. Carbon sequestration in soils. *Journal of Soil and Water Conservation* 54: 382-389.

Buchanan, M. and Gliessman, S. R. 1991. How compost fertilization affects soil nitrogen and crop yield. *Biocycle* 32: 72-77.

Buckerfield, J. and Webster, K. 1999. Compost as mulch for vineyards. *The Australian Grapegrower and Winemaker*: 112-118.

Campbell, C.A. 1978. Soil organic carbon, nitrogen and fertility. In: 'Soil Organic Matter', Eds M. Schniter and S.U. Khan, Elsevier Scientific Publications Co., Amsterdam, pp 173-272.

Campbell, C.A., Selles, F., Lafond, G.P. and Zentner, R.P. 2001. Adopting zero tillage management: Impact on soil C and N under long-term crop rotations in a thin Black Chernozem. *Canadian Journal of Soil Science* 81: 139-148.

Chae, Y. M. and Tabatabai, M. A. 1986. Mineralization of nitrogen in soils amended with organic wastes. *Journal of Environmental Quality* 15: 193-198.

Chan, K.Y. 1989. Effect of tillage on aggregate strength and aggregation of vertisols. *Soil and Tillage Research* 13: 163-175.

Chan, K.Y. 2001. Soil organic carbon and soil structure: implications for the soil health of agrosystems. In: 'Soil Health. The Foundation of Sustainable Agriculture', Proceedings of a workshop on the importance of soil health in agriculture, Ed R. Lines-Kelly, Wollongbar Agricultural Institute, NSW, pp 126-133.

Chan, K.Y., Bowman, A.M. and Oates, A. 2001a. Oxidisible organic carbon fractions and soil quality changes in an Oxic Paleustalf under different pasture leys. *Soil Science* 166: 61-67.

Chan, K.Y., Bowman, A.M., Smith, W. and Ashley, R. 2001b. Restoring soil fertility of degraded hardsetting soils in semi-arid areas with different pastures. *Australian Journal of Experimental Agriculture* 41, 507-514. (table 4.5??)

Chan, K.Y., Heenan, D.P., Grabski, A.S. and So, H.B. 1998. Soil organic carbon sequestration and changes in soil quality under conservation tillage on lighter-textured soils in Australia. In: 'Conservation Tillage : Can it Assist in Mitigating the Greenhouse Gas Problem?' Symposium organised by Australian Soil Science Society Inc and International Soil Tillage Research Organisation, 30 April, 1998, University of Queensland, St Lucia.

Chan, K.Y. and Mullins, C.E. 1994. Slaking characteristics of some Australian and British soils. *European J. of Soil Science* 45: 273-283.

Chan, K. Y. and Pratley, J. 1998. Soil structural declines - how the trend can be reversed ? In: 'Agriculture and the Environmental Imperative', Eds J. Pratley, and A. Robinson, CSIRO: Collingwood, Australia.

Charman, P.E.V., and Roper, M.M. 1991. Soil organic matter. In: 'Soils-their properties and Management: a Soil Conservation Handbook for New South Wales', Eds P.E.V. Charman and B.W. Murphy, Sydney University Press, Australia, 1991, pp 206-214.

Chartre, C.J., Helyar, K.R., Fitzpatrick, R.W. and Williams, J. 1992. Land degradation as a result of European settlement of Australia and its influences on soil properties. In: 'Australia's Renewable Resources: Sustainability and Global Change', Eds R.M. Gifford and M.M. Barson, Bureau of Rural Resources Proceedings No. 14, AGPS, Canberra.

Dalal, R.C. and Chan, K. Y. 2001. Soil organic matter in rainfed cropping systems of Australian cereal belt. *Australian Journal of Soil Research* 39: 435-464.

Dalal, R.C. and Mayer, R.J. 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in Southern Queensland. II total organic carbon and its rate of loss from the soil profile. *Australian Journal of Soil Research* 24: 281-292.

De Bertoldi, M., Ferranti, M. P., L'Hermite, P. and Zucconi, F. 1986. Compost: Production, Quality and Use. Commission of the European Communities. Elsevier Applied Science. pp. 853.

De Ceuster, T.J.J. and Hoitink, H.A.J. 1999a. Prospects for Composts and Biocontrol Agents as Substitutes for Methyl Bromide in Biological Control of Plant Diseases. *Compost Science and Utilisation* 7: 6-15.

De Ceuster, T.J.J. and Hoitink, H.A.J. 1999b. Using Compost to control Plant Diseases. *Biocycle* 40: 61-64.

Dick, W.A. and Tabatabai, M.A. 1992. Potential uses of soil enzymes. In: 'Soil Microbial Ecology', Ed B. Metting, Marcel Dekker, New York, pp. 95-127.

Dumontet, S., Dinel, H., Schnitzer, M., Paré, T. and Scopa, A. 2001. Composting organic residues: Trace metals and microbial pathogens. *Canadian Journal of Soil Science* 81: 357-367.

Edmonds, J.A. 1999. Beyond Kyoto: Towards a technology greenhouse strategy. *Consequences* 5: 17-28.

Edwards, L., Burney, J.R., Richter, G. and MacRae, A.H. 2000. Evaluation of compost and straw mulching on soil-loss characteristics in erosion plots of potatoes in Prince Edward Island, Canada. *Agriculture, Ecosystems and Environment* 81: 217-222.

Emmerling, C., Liebner, C., Haubold-Rosar, M., Katzur, J. and Schroder, D. 2000. Impact of application of organic waste materials on microbial and enzyme activities of mine soils in the Lusatian coal mining region. *Plant and Soil* 220: 129-138.

Eriksen, G.N., Coale, F.J. and Bollero, G.A. 1999. Soil nitrogen dynamics and maize production in municipal solid waste amended soil. *Agronomy Journal* 91: 1009-1016.

Eshwarn, H., Berg, E.V.D. and Reich, P. 1993. Organic carbon in soils of the world. *Soil Science Society of America Journal* 57: 192-194.

Eshwarn, H., Berg, E.V.D., Reich, P. and Kimble, J. 1995. Global soil carbon resources. In: 'Soils and Global Change'. Eds: R. Lal, J. Kimble, E. Levine and B.A. Stewart, CRC, Lewis Publishers, pp. 27-29.

Fauci, M.F. and Dick, R.P. 1994. Plant response to organic amendments and decreasing inorganic nitrogen rates in soils from a long-term experiment. *Soil Science Society of America Journal* 58: 134-138.

Fahy, P. and Richard, S. 2000. Biosolids and Greenwaste Composts: development of safe, sustainable markets. Report to Sydney Water Corporation, Waste Service NSW and Australian Native Landscapes, January 2000. NSW Agriculture Organic Waste Recycling Unit, pp 114.

Felton, W., Schwenke, G., Martin, R. and Fisher, J. 2000. Changes in carbon in summer rainfall cropping systems. In: Workshop Proceedings 'Management Options for Carbon Sequestration in Forest, Agricultural and Rangeland Ecosystems', CRC for Greenhouse Accounting, 25 May 2000, pp 32-37.

Fisher, R.F. 1995. Soil organic matter: clue or conundrum. In: 'Carbon Forms and Functions in Forest Soils', Soil Science Society of America, Eds W.W. McFee and J. M. Kelly, CRC Inc, Madison, USA. 594: 1-11.

Francis, J. 1999. Establishing and measuring carbon sequestration. *Australian Farm Journal* 9: 45-47.

Gallardo-Lara, F. and Nogales, R. 1987. Effect of the application of town refuse compost on the soil-plant system: a review. *Biological Wastes* 19: 35-62.

Garcia, C., Hernandez, T. and Costa, F. 1991. Agronomic value of urban waste and the growth of ryegrass (*Lolium perenne*) in a Calcithorid soil amended with this waste. *Journal of the Science of Food and Agriculture* 56: 457-467.

Garcia, C., Hernandez, T., Costa, F. and Ceccanti, B. 1994. Biochemical parameters in soils regenerated by the addition of organic wastes. *Waste Management and Research* 12: 457-466.

Garcia-Gil, Plaza, C., Soler-Rovira, P. and Polo, A. 2000. Long-term effects of municipal solid waste compost application on soil enzyme activities and microbial biomass. *Soil Biology and Biochemistry* 32: 1907-1913.

Geeves, G.W., Cresswell, H.P., Murphy, B.W., Gessler, P.E., Chartres, C.J., Little, I.P. and Bowman, G.M. 1995. The physical, chemical and morphological properties of soils in the wheatbelt of southern NSW and northern Victoria. Department of Conservation and Land Management/ CSIRO Australian Division of Soils, Occasional Report.

Giusquiani, P.L., Gigliotti G. and Businelli, D. 1994. Long term effects of heavy metals from composted municipal waste on some enzyme activities in a cultivated soil. *Biological Fertility of Soils* 17: 257-262.

Giusquiani, P.L., Pagliai, M., Gigliotti, G., Businelli, D. and Benetti, A. 1995. Urban waste compost: Effects on physical, chemical, and biochemical soil properties. *Journal of Environmental Quality* 24: 175-182.

Goulding, K.W.T., Murphy, D.V., Macdonald, A., Stockdale, E.A., Gaunt, J.L., Blake, L., Ayaga, G. and Brookes, P. 1999. The role of soil organic matter and manures in sustainable nutrient cycling. In: 'Sustainable Management of Soil Organic Matter', Eds R.M. Rees, B.C. Ball, C.D. Campbell and C.A. Watson, CAB International. 440: 221-232. Sect 4.2

Guidi, G., Pera, A., Giovannetti, M., Poggio, G. and Bertoldi, M. 1988. Variations of soil structure and microbial population in a compost amended soil. *Plant and Soil* 106: 113-119.

Halvorson, A. D., Reule, C. A. and Follett, R. F. 1999. Nitrogen fertilization effects on soil carbon and nitrogen in a dryland cropping system. *Soil Science Society of America Journal* 63: 912-917.

Hao, Y. L., Lal, R., Izaurralde, R. C., Ritchie, J. C., Owens, L. B. and Hothem, D. L. 2001. Historic assessment of agricultural impacts on soil and soil organic carbon erosion in an Ohio watershed. *Soil Science* 166: 116-126.

Hartz, T. K., Mitchell, J. P. and Giannini, C. 2000. Nitrogen and carbon mineralization dynamics of manures and composts. *Hortscience* 35: 209-212.

Hassall and Associates. 2001. The Carbon Farmer Model. A report for the Rural Industries Research and Development Corporation, Australia.

Hassink, J. 1992. Effects of soil texture and structure on carbon and nitrogen mineralization in grassland soils. *Biology and Fertility of Soils* 14: 126-34.

Hazelton, P. and Murphy, B. 1992. What do all the Numbers Mean? A Guide for the Interpretation of Soil Test Results. Department of Conservation and Land Management, Sydney.

He, Z. L., Alva, A. K., Yan, P., Li, Y., Calvert, C. D., Stoffella, V. P. J. and Banks, D. J. 2000. Nitrogen mineralization and transformation from composts and biosolids during field incubation in a sandy soil. *Soil Science* 165: 161-169.

Heenan, D. P., McGhie, W. J., Thompson, F. and Chan, K.Y. 1996. Decline in soil organic carbon and total nitrogen in relation to tillage, stubble management and rotation. *Australian Journal of Experimental Agriculture* 35: 877-884.

Hegarty, R. 2001. Greenhouse gas emissions from the Australian livestock sector. What do we know, what can we do? Australian Greenhouse Office, Canberra, October 2001, pp. 32.

Hernando, S., Lobo, M. C. and Polo, A. 1989. Effect of the application of municipal refuse compost on the physical and chemical properties of a soil. *Science of the Total Environment* 81, 82: 589-596.

Hoitink, H.A.J. and Boehm, M.J. 1999. Biocontrol within the context of soil microbial communities: A substrate-dependent phenomenon. *Annual Review of Phyopathology* 37: 427-446.

Hoitnik, H.A.J. and Keener, H.M. 1992. Science and Engineering of Composting. Design, Environmental, Microbial and Utilisation Aspects. Ohio State University. Renaissance Publications, pp. 728.

Hoitink, H.A.J. and Fahy, P.C. 1986. Basis for the control of soilborne plant pathogens with composts. *Annual Review of Phyopathology* 24: 93-114.

Holloway, R. 1998. Carbon Credits-an alternative income from trees. *Trees and Natural Resources. December: 23-24.*

Hortenstine, C. C. and Rothwell, D. F. 1968. Garbage compost as a source of plant nutrients for oats and radishes. *Florida Agricultural Experiment Stations Journal Series Paper No. 2964* Summer: 23-25.

Hortenstine, C. C. and Rothwell, D. F. 1973. Pelletized municipal refuse compost as a soil amendment and nutrient source for sorghum. *Journal of Environmental Quality*: 2: 343-345.

Ibrahim, S. M. and Shindo, H. 1999. Effect of continuous compost application on water-stable soil macroaggregation in a field subjected to double cropping. *Soil Science and Plant Nutrition.* 45:1003-1007.

Iglesias-Jimenez, E. and Alvarez, C. E. 1993. Apparent availability of nitrogen in composted municipal refuse. *Biology and Fertility of Soils* 16: 313-318.

Illera, V., Walter, I., Cuevas, G. and Cala, V. 1999. Biosolid and municipal solid waste effects on physical and chemical properties of a degraded soil. *Agrochimica* 43: 178-86.

Inbar, Y., Chen, Y. and Hadar, Y. 1990. Humic substances formed during the composting of organic matter. *Soil Science Society of America Journal*. 54: 1316-1323.

IPCC, 2002. Land Use, Land Use Change and Forestry. Chapter 2. Implications of Different Definitions and Generic Issues. International Panel on Climate Change. Internet publication: http://www.grida.no/climate/ipcc/land_use/.

Isbell, R.F. 1996. The Australian Soil Classification. CSIRO Publishing, pp 143.

Isbell, R.F., McDonald, W.S. and Ashton, L.J. 1997. Concepts and Rationale of the Australian Soil Classification, ACLEP, CSIRO Land and Water, Canberra, pp152.

Izaurralde, R. C., Rosenberg, N. J. and Lal, R. 2001. Mitigation of climatic change by soil carbon sequestration: Issues of science, monitoring, and degraded lands. *Advances in Agronomy* 70: 1-75.

Jackson, M. 1998. The Greenhouse Challenge for Australia. Symposium on 'Conservation Tillage: Can it assist in mitigating the greenhouse gas problem?' University of Queensland, April, 1998.

Jenkinson, D.S. 1988. Soil organic matter and its dynamics. In : Russell's 'Soil Conditions and Plant Growth', Ed A. Wild, Longman, Essex, pp 564-607.

Jenkinson, D.S. 1991. The Rothamsted long-term experiments: are they still of use? *Agron. Journal* 83: 2.

Jenkinson, D.S. and Rayner, J.H. 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. *Soil Science* 123: 298-305.

Jobbagy, E.G. and Jackson, R.B. 2000. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications* 10: 423-436.

Johnson, M.G. 1995. The role of soil management in sequestering soil carbon. In: 'Soil Management and Greenhouse Effect', Eds R. Lal, J. Kimble, E. Levine and B. A. Stewart, Advances in Soil Science, CRC Press, Boca Raton, pp 351- 363.

Khaleel, R., Reddy, K. R. and Overcash, M. R. 1981. Changes in soil physical properties due to organic waste applications: a review. *Journal of Environmental Quality* 10: 133-141.

Kimble, J.M., Eswaran, H. and Cook, T. 1990. Organic carbon on a volume basis in tropical and temperate soils. *Transactions of the International Congress of Soil Science*, Koyoto 5: 248-253.

Kumar, S., Malik, R. S. and Dahiya, I. S. 1985. Influence of different organic wastes upon water retention, transmission and contact characteristics of a sandy soil. *Australian Journal of Soil Research* 23: 131-136.

Lal, R. 1997. Residue management, conservation tillage and soil restoration for mitigating greenhouse effect by CO2- enrichment. *Soil and Tillage Research* 43: 81-107.

Lal, R. and Bruce, J.P. 1999. The potential of world cropland soils to sequester C and mitigate the greenhouse effect. *Environmental Science and Policy* 2: 177-185.

Lal, R., Kimble, J.M., Follett, R.F. and Stewart, B.A. 1998a. Soil Processes and the Carbon Cycle. CRC Press LLC, MA USA, pp 609.

Lal, R., Kimble, J.M. and Follett, R.F. 1998b. Land use and soil C pools in terrestrial ecosystems. In: 'Management of Carbon Sequestraton in Soil', Eds R. Lal, J.M. Kimble, R.F. Follett, and B.A Stewart, CRC Press, New York. 457: 1-10.

Lal, R., Kimble, J., Levine, E. and Whitman, C. 1995. World soils and greenhouse effect: an overview. In: 'Soils and Global Change', Eds R. Lal, J. Kimble, E. Levine and B.A. Stewart, Lewis Publishers, CRC Press Inc., Florida, USA.

Love, E.J. and Rochfort , C.J. 1999. Markets for Products Containing Recycled Organics Materials. Report prepared for the NSW Waste Boards, March 1999.

Mamo, M., Molina, J. A. E., Rosen, C. J. and Halbach, T. R. 1999. Nitrogen and carbon mineralization in soil amended with municipal solid waste compost. *Canadian Journal of Soil Science* 79: 535-542.

Martens, D. A. 2000. Plant residue biochemistry regulates soil carbon cycling and carbon sequestration. *Soil Biology and Biochemistry* 32: 361-369.

Martens, D. A. and Frankenberger, Jr. W. T. 1992. Modification of infiltration rates in an organic-amended irrigated soil. *Agronomy Journal* 84: 707-717.

Martin, J.P., Martin, W.P., Page, J.B., Raney, W.A. and Dement, J.D 1955. Soil aggregation. *Advances in Agronomy* 7: 1-38.

Maynard, A. A. 1999. Reducing fertilizer costs with leaf compost. *BioCycle* 40: 54-55.

Mays, D. A. and Giordano, P. M. 1989. Landspreading municipal waste compost. *Biocycle* 30: 37-39.

Mays, D. A., Terman, G. L. and Duggan, J. C. 1973. Municipal compost: effects on crop yields and soil properties. *Journal of Environmental Quality* 2: 89-92.

McConnell, D. B., Shiralipour, A. and Smith, W. H. 1993. Compost application improves soil properties. *Biocycle* 34: 61-63.

McKenzie, N., Ryan, P., Fogarty, P. and Wood, J. 2000. Sampling, measurement and analytical protocols for carbon estimation in soil, litter and coarse woody debris. National Carbon Accounting System Technical Report No. 14, Australian Greenhouse Office. Internet publication http://www.greenhouse.gov.au/ncas/files/consultancies/soilchange/soils.html.

Metherell, A.K., Harding, L.A., Cole, C.V. and Parton, W.J. 1993. CENTURY - Soil Organic Matter Model Environment. Technical Documentation Agroecosystem Version 4.0. Great Plains System Research Unit, Technical Report No. 4, USDA-ARS, Fort Collins, Colorado.

Mohavedi, S.A.R. and Cook, H.F. 2000. Influence of municipal waste compost amendment on soil water and evaporation. *Communications in Soil Science and Plant Analysis* 31: 3147-3161.

Naeini, S.A.R.M. and Cook, H. F. 2000. Influence of municipal waste compost amendment on soil water and evaporation. *Communications in Soil Science and Plant Analysis 31: 3147-3161*.

Neilsen, G. H., Hogue, E. J., Neilsen, D. and Zebarth, B. J. 1998. Evaluation of organic wastes as soil amendments for cultivation of carrot and chard on irrigated sandy soils. *Canadian Journal of Soil Science* 78: 217-225.

Nolan ITU 1999. Green Waste Market Development Program. Phase B: Supply forecast and Phase C: Strategic phasing of garden waste ban. Report to the NSW Waste Boards, March 1999, pp 61-73.

Northcote, K.H. 1983. Soil: A National Resource. In: 'Man and the Australian Environment - Current issues and viewpoints', Eds W. Hanely and M. Cooper. Chapter 1, pp. 3-23. McGraw- Hill Book : Sydney.

NSW Department of Land and Water Conservation 2000. Taking on the challenge - NSW Salinity Strategy. New South Wales Government.

NSW EPA 1997. Environmental Guidelines, Use and Disposal of Biosolids Products. New South Wales, Environment Protection Authority, Australia.

NSW EPA 2000. State of the Environment Report, Chapter 4: Land. New South Wales Environment Protection Authority, Australia.

Oades, J. M. 1984. Soil organic matter and structural stability: mechanisms and implications for management. *Plant and Soil* 76: 319-337.

Oades, J. M. 1988. The retention of organic matter in soils. *Biogeochemistry* 5: 35-70.

Ouedraogo, E., Mando, A. and Zombre, N. P. 2001. Use of compost to improve soil properties and crop productivity under low input agricultural system in West Africa. *Agriculture Ecosystems and Environment. 84: 259-266*.

Pagliai, M., Guidi, G., La Marca, M., Giachetti, M. and Lucamante, G. 1981. Effects of sewage sludges and composts on soil porosity and aggregation. *Journal of Environmental Quality* 10: 556-561.

Parton, W. J., Schimel, D. S., Cole, C. V. and Ojima, D. S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains Grasslands. *Soil Science Society of America Journal* 51: 1173-1179.

Pascual, J. A., Garcia, C. and Hernandez, T. 1999a. Comparison of fresh and composted organic waste in their efficacy for the improvement of arid soil quality. *Bioresource Technology* 68: 255-264.

Pascual, J. A., Garcia, C. and Hernandez, T. 1999b. Lasting microbiological and biochemical effects of the addition of municipal solid waste to an arid soil. *Biology and Fertility of Soils* 30: 1-6.

Paul, E.A. and van Veen, J. 1978. The use of tracers to determine the dynamics nature of organic matter. *Transactions of the 11th International Congress of Soil Science* 3: 61-102.

Paul, K., Polglase, P., Coops, N., O'Connell, T., Grove, T., Mendham, D., Carlyle., May, B., Smethurst, P. and Baillie, C. 2002. Modelling Change in Soil Carbon Following Afforestation or Reforestation. Preliminary simulations using GRC3 and sensitivity analysis. National Carbon Accounting System Technical Report No. 29, Australian Greenhouse Office. Internet publication http://www.greenhouse.gov.au/ncas/files/consultancies/soilchange/ soils.html.

Pera, A., Vallini, G., Sireno, I., Bianchin, M. L. and de Bertoldi, M. 1983. Effect of organic matter on rhizosphere microorganisms and root development of Sorghum plants in two different soils. *Plant and Soil* 74: 3-18.

Perucci, P. 1993. Enzyme activity and microbial biomass in a field soil amended with municipal refuse. *Biology and Fertility of Soils* 14: 54-60.

Piao, H. C., Liu, G. S., Wu, Y. Y. and Xu, W. B. 2001. Relationships of soil microbial biomass carbon and organic carbon with environmental parameters in mountainous soils of southwest China. *Biology and Fertility of Soils* 33: 347-350.

Pinamonti, F. 1998. Compost mulch effects on soil fertility, nutritional status and performance of grapevine. *Nutrient Cycling in Agroecosystems* 51: 239-248.

Pinamonti, F., Zorzi, G., Gasperi, F., Silvestri, S. and Stringari, G. 1995. Growth and nutritional status of apple trees and grapevines in municipal solid-waste-amended soil. *Acta Horticulturae* 383: 313-321.

Post, W. M. and Kwon, K. C. 2000. Soil carbon sequestration and land-use change: processes and potential. *Global Change Biology* 6: 317-327.

Post, W.M., Peng, T.H., Emanuel, W.R., King, A.W., Dale, V.H. and DeAngelis, D.L. 1990. The global carbon cycle. *American Scientist* 78: 310-326.

Potter, K. N., Torbert, H. A., Johnson, H. B. and Tischler, C. R. 1999. Carbon storage after long-term grass establishment on degraded soils. *Soil Science* 164: 718-725.

Poulton, P.R. 1995. The importance of long-term trials in understanding sustainable farming systems: the Rothamsted experience. *Australian Journal of Experimental Agriculture* 35: 825-834.

Press, C. M., Mahaffee, W. F., Edwards, J. H. and Kloepper, J. W. 1996. Organic by-product effects on soil chemical properties and microbial communities. *Compost Science and Utilization* 4: 70-80.

Pretty, J. and Ball, A. 2001. Agricultural influences on carbon emissions and sequestration: a review of evidence and the emerging trading options. *Centre for Environment and Society, Occasional Paper 2001-03, University of Essex*, U.K.

Rahn, C.R. and Lillywhite, R.D. 2002. A study of the quality factors affecting the short-term decomposition of field vegetable residues. *Journal of the Science of Food and Agriculture* 82: 19-26.

Rasmussen, P.E. and Albrecht, S.L. 1998. Crop management effects on organic carbon in semi-arid Pacific Northwest soils. In: 'Management of carbon sequestration in soil', Eds R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart, CRC Press LLC, Florida, USA.

Rickman, R.W., Douglas, C.L., Albrech, S.L., Bundy, L.G. and Berc, J.L. 2001. CQESTR: A model to estimate carbon sequestration in agricultural soils. *Journal of Soil and Water Conservation* 56: 237-242.

Rosenzweig, C. and Hillel, D. 2000. Soils and global climate change: Challenges and opportunities. *Soil Science* 165: 47-56.

Rosell, R.A. and Galantini, J.A. 1998. Soil organic carbon dynamics in native and cultivated ecosystems of South America. In: 'Management of carbon sequestration in soil', Eds R. Lal, J.M. Kimble, R.F. Follett and B.A. Stewart. CRC Press LLC, Florida, USA, pp 11-33.

Rothwell, D. F. and Hortenstine, C. C. 1969. Composted municipal refuse: Its effects on carbon dioxide, nitrate, fungi, and bacteria in Arredondo Fine Sand. *Agronomy Journal* 61: 837-840.

ROU 2001. Greenhouse gas emissions from composting facilities. Recycled Organic Unit, University of New South Wales, Sydney, Australia. Report prepared for Central Coast Waste Board, NSW.

ROU 2002. Guide to Manufacturing Value-Added Recycled Organics Products for Markets. Recycled Organic Unit, University of New South Wales, Sydney, Australia. Draft Report prepared for Resource NSW.

Schlesinger, W. H. 1990. Evidence from chronosequence studies for a low carbon-storage potential of soils. *Nature* 348: 232-234.

Schlesinger, W. H. 1996. Biogeochemistry-An Analysis of Global Change, Academic Press. pp 359.

Schlesinger, W. H. 1999. Carbon sequestration in soils. *Science* 284: 2095.

Schlesinger, W. H. 2000. Carbon sequestration in soils: some caution amidst optimism. *Agriculture, Ecosystems and Environment* 82: 121-127.

Schlesinger, W. H. and Andrews, J. A. 2000. Soil respiration and the global carbon cycle. *Biogeochemistry* 48: 7-20.

Semple, K. T., Reid, B. J. and Fermor, T. R. 2001. Impact of composting strategies on the treatment of soils contaminated with organic pollutants. *Environmental Pollution* 112: 269-283.

Sherwood, S., and Uphoff, N. 2000. Soil health: research, practice and policy for a more regenerative agriculture. *Applied Soil Ecology* 15: 85-97.

Shiralipour, A., McConnell, D. B. and Smith, W. H. 1992a. Physical and chemical properties of soils as affected by municipal solid waste compost application. *Biomass and Bioenergy* 3: 261-266.

Shiralipour, A., McConnell, D. B. and Smith, W. H. 1992b. Uses and benefits of MSW compost: a review and an assessment. *Biomass and Bioenergy* 3: 267-279.

Sikora, L.J. and Enkiri, N.K. 2001. Uptake of ^{15}N fertiliser in compost-amended soils. *Plant and Soil*. 235: 65-73.

Sikora, L. J. and Yakovchenko, V. 1996. Soil organic matter mineralization after compost amendment. *Soil Science Society of America Journal* 60: 1401-1404.

Six, J., Paustian, K., Elliott, E. T. and Combrink, C. 2000. Soil structure and organic matter: I. Distribution of aggregate-size classes and aggregate-associated carbon. *Soil Science Society of America Journal* 64: 681-689.

Skjemstad, J. 2000. Agricultural Management Practices. In: Workshop proceedings ‘Management Options for Carbon Sequestration in Forest, Agricultural and Rangeland Ecosystems’, CRC For Greenhouse Accounting, 25 May 2000, pp. 54.

Skjemstad, J. O., Dalal, R. C., Janik, L. J. and McGowan, J. A. 2001. Changes in chemical nature of soil organic carbon in Vertisols under wheat in south-eastern Queensland. *Australian Journal of Soil Research 39: 343-359*.

Skjemstad, J. O., Janik, L. J. and Taylor, J. A. 1998. Non-living soil organic matter: what do we know about it? *Australian Journal of Experimental Agriculture* 38: 667-680.

Skjemstad, J. O., Spouncer, L.R. and Beech, A. 2000. Carbon Conversion Factors for Historical Soil Carbon Data. National Carbon Accounting System Technical Report No. 15, Australian Greenhouse Office. Internet publication http://www.greenhouse. gov.au/ncas/ files/consultancies/ soilchange/soils.html.

Smith, K.A. 1999. After the Kyoto Protocol: Can soil scientists make a useful contribution? *Soil Use and Management* 15: 71-75.

Smith, P., Powlson, D. S., Smith, J. U., Falloon, P. and Coleman, K. 2000a. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology* 6: 525-539.

Smith, W. N., Desjardins, R. L. and Pattey, E. 2000b. The net flux of carbon from agricultural soils in Canada 1970-2010. *Global Change Biology* 6: 557-568.

Smith, W. N., Desjardins, R. L. and Grant, B. 2001. Estimated changes in soil carbon associated with agricultural practices in Canada. *Canadian Journal of Soil Research* 81: 221-227.

Soil Science Society of America 1996. Glossary of Soil Science Terms. Soil Science Society of America Inc., Wis., USA

Soil Survey Staff, 1994. Keys to Soil Taxonomy, 6th Edition. Soil Conservation Service, USDA, Washington, DC.

Spain, A.V., Isbell R.F. and Probert, M.E. 1983. Soil organic matter. In: 'Soils: An Australian Viewpoint', CSIRO, Melbourne, Academic Press, London, pp 551-563.

Sparling, G.P. 1992. Ratio of microbial biomass carbon to soil organic-carbon as a sensitive indicator of changes in soil organic matter. *Australian Journal of Soil Research* 30: 195-207.

Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J. and Hallsworth, E.G. 1968. A Handbook of Australian Soils. Rellim Technical Publications, Glenside, South Australia, pp 435.

Stamatiadis, S., Werner, M. and Buchanan, M. 1999. Field assessment of soil quality as affected by compost and fertilizer application in a broccoli field (San Benito County, California). *Applied Soil Ecology* 12: 217-225.

Standards Australia 1999. Australian Standard AS 4454-1999. Composts, soil conditioners and mulches.

Stevenson, F.J. 1986. Carbon balance of the soil and role of organic matter in soil fertility. In: 'Cycles of Soil - Carbon, Nitrogen, Phosphorus, Sulphur, Micro-nutrients'. John Wiley & Sons, pp 45-77.

Stirling, M. 2001. Soil biology and its importance in soil health. In: 'Soil Health. The Foundation of Sustainable Agriculture'. Proceedings of a workshop on the importance of soil health in agriculture, Ed R. Lines-Kelly, Wollongbar Agricultural Institute, NSW, pp 24-29.

Stockdale, E. A., Lampkin, N. H., Hovi, M., Keating, R., Lennartsson, E. K. M., Macdonald, D. W., Padel, S., Tattersall, F. H., Wolfe, M. S. and Watson, C. A. 2001. Agronomic and environmental implications of organic farming systems. *Advances in Agronomy* 70: 261-327.

Stockfisch, N., Forstreuter, T. and Ehlers, W. 1999. Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. *Soil and Tillage Research* 52: 91-101.

Subak, S. 2000. Agricultural soil carbon accumulation in North America: considerations for climate policy. *Global Environmental Change* 10: 185-195.

Swift, R.S. 2001. Soil organic carbon - potential for sequestration and recycling. Workshop on Recycled Organics – Partnerships, Processes and Products, 25-27 September 2001, University of Queensland, Gatten, pp 21-27.

Sydney Water 2000. Annual Environment and Public Health Report 2000. Sydney Water Corporation, p 36.

Tisdall, J. M. and Oades, J. M. 1982. Organic matter and water-stable aggregates in soils. *Journal of Soil Science* 33: 141-163.

Turner, M. S., Stanley, G. A., Smajstrla, C. D. and Clark, A. G. 1994. Physical characteristics of a sandy soil amended with municipal solid waste compost. *Soil and Crop Science Society of Florida Proceedings* 53: 24-26.

Uri, N. D. and Bloodworth, H. 2000. Global climate change and the effect of conservation practices in US agriculture. *Global Environmental Change* 10: 197-209.

Van Bruggen, A.H.C. and Semenov, A.M. 2000. In search of biological indicators for soil health and disease suppression. *Applied Soil Ecology*. 15:13-24.

Volk, B.G. and Loeppert, R.H. 1982. Soil organic matter. In: 'Handbook of Soils and Climate in Agriculture', Eds. V.J. Kilmer and A.A. Hanson, CRC Press, Inc. Boca Raton, Florida.

Webb, A. (Ed) 2002. Pre-clearing Soil Carbon Levels in Australia. National Carbon Accounting System Technical Report No. 12, Australian Greenhouse Office. Internet publication http://www.greenhouse.gov.au/ncas/files/consultancies/soilchange/soils.html.

Webbnet Land Resources Services Ltd 1999. Estimation of Changes in Soil Carbon due to Changes Land Use. National Carbon Accounting System Technical Report No. 2, Australian Greenhouse Office. Internet publication http://www.greenhouse.gov.au/ncas/files/consultancies/ soilchange/soils.html.

Wells, A.T., Chan, K.Y. and Cornish, P.S. 2000. Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales. *Agricultural Ecosystem and Environment* 80: 47-60.

Wilkinson, K., Tee, E. and Hood, V. 2000. Does AS 4454 adequately benchmark compost quality? Proceedings of the Compost 2000 Down Under Conference, 14-15 November 2000, Melbourne, Vic.

Wong, P. 2001. Role of organic amendments in disease control. In: ‘Soil Health. The Foundation of Sustainable Agriculture’. Proceedings of a workshop on the importance of soil health in agriculture, Ed R. Lines-Kelly, Wollongbar Agricultural Institute, NSW, pp 45-50.

Yang, X. M. and Wander, M. M. 1999. Tillage effects on soil organic carbon distribution and storage in a silt loam soil in Illinois. *Soil and Tillage Research* 52: 1-9.

Zebarth, B. J., Neilsen, G. H., Hogue, E. and Neilsen, D. 1999. Influence of organic waste amendments on selected soil physical and chemical properties. *Canadian Journal of Soil Science* 79: 501-4.

Zinati, G. M., Li, Y. C. and Bryan, H. H. 2001.Utilization of compost increases organic carbon and its humin, humic and fulvic acid fractions in calcareous soil. *Compost Science and Utilization 9: 156-162*.

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Appendix

Table A1 Classification systems for soil types [adapated from Isbell, (1996), with soil properties and land uses derived from Isbell *et al*., (1997)]. The order of the Australian Soil Classification groups is approximately the order in which the soils occur, from highest to lowest incidence within NSW.

Australian Soil Classification	Great Soil Group	US Soil Taxonomy	Soil Properties	Land Uses (in NSW)
Sodosols (there are no direct equivalents because of the way the soils were classified)	• solonetz • solodized solonetz • solodic soils • soloths and red brown earths • podzolics • desertloams	• Alfisols • Ultisols • Aridisols	• Waterlogging and/or low water holding capacity • Root penetration problems • Impermeable sodic clay B horizon • A horizon – low chemical fertility • Can be hardsetting • Dispersive subsoils • Prone to erosion	• Grazing – dryland and irrigated • Forestry • Cereal production
Kandosols	• Red, yellow and grey earths • calcareous red earths	• Alfisols • Ultisols • Aridisols	• Good drainage • Adverse surface soil physical properties, eg. hardsetting, crusting	• Cereal cropping • Citrus • Horticulture • Cut flowers • Cattle grazing
Vertosols	• Black earths • Grey, brown and red clays • Some Rendzinas, chernozems, prairie and wiesenboden soils	• Haplusterts • Haplotorrerts	• Restricted water infiltration • High Na common in upper profile	• grazing of native and improved pastures • wheat, sorghum and cotton most important dryland crops • rice, sugarcane and cotton – irrigated crops
Calcarosols	• Solonised brown soils • Grey-brown and red calcareous soils	• Aridisols (mainly Calcids and Arigids) • Alfisols (mainly Rhodoxeralfs and Palexeralfs) • Inceptisols (mainly Xerochrepts)	• Shallow depth • Low water retention due to hard carbonate • Wind erosion on sandier surface soils • High salinity & alkalinity	• Irrigated horticulture (especially vines) along the Murray River
Chromosols	• Non calcic brown soils • Red-brown earths • Podzolics	• Non-sodic Alfisols and Aridisols	• Virgin soils usually have favourable physical properties • Hardsetting surface soils with structural degradation	• Cereal and oil seed production
Dermosols	• Prairie soils	• Mollisols	• Surface soils often contain gravel	• Cereal cropping

Australian Soil Classification	Great Soil Group	US Soil Taxonomy	Soil Properties	Land Uses (in NSW)
	• Chocolate soils • Rendzinas • Terra rossa • Red and yellow podzolics	• Alfisiols • Utisols • Vertisols		• Forest plantations • Rainforests (national parks)
Tenosols	• Lithosols • Siliceous sands • Alluvial soils • Earthy sands • Alpine humus soils	• Aridisols (Cambids, Argids, Durids) • Enitsols	• Poor water retention • Low fertility	• Native pastures – sheep and cattle grazing
Kurosols	• Podzolics • Soloths	• Ultisols • Alfisols	• High subsoil exchanfeable magnesium • High degree of mottling	• Forest plantations • Improved pasture (dairying) • Cattle grazing
Rudosols	• alluvials • lithosols • siliceous sands • calcareous sands • solonchaks	• mainly Entisols • salic Aridisols	• undeveloped soil profile	• cattle and sheep grazing • irrigated citrus and vines (Riverine Plain)
Ferrosols	• Krasnozems • Euchrozems • Chocolate soils	• Oxisols • Alfisols • Mollisols	• Favourable physical properties • Degrade under cropping • Erosion, compaction and acidification	• Improved pastures (dairying) • Horticultural crops • Potatoes

Hydrosols	• Solonchaks
	• Humic gleys
	• Gleyed podzolics
	• Some alluvials
	• Yellow and grey earths
		• The aquic suborders of:
		  • Alfisols
		  • Ultisols
		  • Inceptisols
		  • Entisols
		• salic Aridisols
			• Poor drainage
			• Salinisation
			• Acidification (with acid sulphate soils)
				• Sugarcane
				• Cereal cropping

Podosols	• Podzols • Humus podzols • Peaty podzols	• Entisols • Some Spodosols	• Low fertility • Poor moisture retention • Seasonal waterlogging	• National parks • Improved pastures (cattle and sheep) • mining
Organosols	• Peats	• Organosols	• Wet drainage depression areas	• National parks (Snowy Mountains area)

Table A2 Physical and chemical requirements for composted products (Source: Standards Australia 1999)

Characteristic and unit of measurement	Soil conditioners and fine mulches (soil amendment)	Mulch (surface application)
PH Total $CaCO_3$ (% dry matter)	5.0 to 7.5 if pH > 7.5 determine total $CaCO_3$	5.0 to 7.5 if pH > 7.5 determine total $CaCO_3$)
Electrical conductivity (dS/m)	No limit	No limit
Phosphorus, soluble (mg/L)	≤5 for products used for P sensitive plants No requirements otherwise	≤5 for products used for P sensitive plants No requirements otherwise
Phosphorus, total (% dry matter)	≤0.1 for products used for P sensitive plants No requirements otherwise	≤0.1 for products used for P sensitive plants No requirements otherwise
Ammonium-N (mg/L)	<300	<300
Ammonium-N plus nitrate-N (mg/L)	>100 if a contribution to plant nutrition is required	No requirement
Nitrogen, total (% dry matter)	>0.8 if a contribution to plant nutrition is required	>0.8 if a contribution to plant nutrition is required
Organic matter content (% dry matter)	≥25	≥25
Boron (mg/kg dry matter)	<200 products with total B of <100 can have unrestricted use	<200 products with total B of <100 can have unrestricted use
Sodium (% dry matter)	<1 or at least 7.5 moles calcium plus magnesium for each mole of sodium in the dry matter	No requirements
Wettability (minutes)	<7	No requirements
Toxicity index (%)	≥60 for all products except those labelled as manure	No requirements
Particle size grading Maximum size (mm) Tolerance (% mass)	 ≤15 Not more than 15% by mass in the shortest dimension to be retained by the sieve	 ≥15 Not less than 70% to be retained by the sieve
Chemical contaminants (heavy metals and organic contaminants	Comply with current national guidelines for unrestricted use	Comply with current national guidelines for unrestricted use
Moisture content (%)	Minimum 25 Maximum = % organic matter + 6 if OM >40% Maximum = % organic matter + 10 if OM <40%	No requirement
Contaminants (% dry matter (w/w) Glass, metal and rigid plastics > 2mm Plastics - Light, flexible or film > 5mm Stones and lumps of clay ≥ 5mm	 ≤0.5 ≤0.05 ≤5	 ≤0.5 ≤0.05 ≤5
NDI_{ISO}	>0 or >0.5 if a contribution to plant nutrition is claimed	>0 or >0.5 if a contribution to plant nutrition is claimed
Self heating	No requirement ≤40°C is advised	No requirement

Table A3 Effects of soil amendment with RO on soil biological properties

Organic amendment type and application rate	Soil type and duration of experiments	Results	References
MSW compost, chicken manure, cow manure and sewage sludge	Fine sand (incubation experiments)	Increasing rates of MSW compost increased fungal and bacterial numbers. CO_2 evolved and nitrification was low for MSW compost.	Rothwell and Hortenstine (1969); USA
MSW Compost (24 t/ha/yr); Sewage sludge (24 t/ha/yr); Ovine manure (24 t/ha/yr); vermicompost (2.4 t/ha/yr and Humic acids (100 l/ha/yr)	Sandy silt loam (Xerorthent) 6 years field investigations	MSW compost enhanced soil enzymatic activity more than other treatments.	Albiach *et al. (* 2000); Spain
Mineral fertiliser, Farm yard manure; Compost 1 supplying 100 kg/ha N; Compost 2 supplying 200 kg/ha N; Compost 3 supplying 300 kg/ha N; Surface applied and then ploughed	Calcic Cambisol 2 years field study	Variations were observed for mycorrhizal infection and aerobic cellulytic microrganism. Micro-organisms were influenced by higher doses of compost. The stability of soil structure increased in coincidence with the increased activity of cellulytic microorganisms and vesicular-arbuscolar mycorrhizae. Soil microrganisms may therefore have stabilised pore walls while microorganisms remained active in the soil.	Guidi *et al.* (1988); Italy
Non composted MSW+poultry litter; Noncomposted MSW+NH4NO3 Two application in fall and spring	Sandy loam (Typic Hapludults) Field and greenhouse experiments	Both amendments reduced Bacillus species of bacteria. MSW+NH4NO3 resulted in a shift to Gram positive bacteria while MSW+ poultry litter resulted in a shift to Gram negative bacteria. Shift to Gram negative bacteria may benefit plant growth and be a useful indicator of soil quality.	Press *et al.(* 1996); USA
Organic fraction of MSW at 6.5 kg/m2 and 26 kg/m2 incorporated into top 20 cm soil	Arid soil (Xeric Torriortents) Field experiments	Organic amendments increased organic matter, showed higher values for microbial biomass C, soil basal respiration and dehydrogenase activity. Higher rates of organic amendments had positive effect on the activity of enzymes responsible for C, N and P cycles particularly at higher rates.	Pascual *et al.* (1999)b; Spain
Sewage sludge (5t/ha and 10 dm t/ha); Coal ash (25 dm t) + sewage sludge (50 or 100 dm t/Ha); Composted sewage sludge less maturity (25 dm t/ha) and composted sewage sludge higher maturity (25 dm t/ha) Applied to 30 cm depth	Tertiary carboniferous sand and loamy sand (coal mine site) Two years lysimeter trial	Microbial activity was low initially but microbial respiration and enzyme activities increased significantly with increased application rates due to increase in OM, nutrient contents of soil and soil physical properties (nutrient and water retension capcity). Highest amounts of microbial and and enzyme activities were measured after application of N rich sewage sludge or very high rates of mature green waste based compost (~250t/ha). However composted sewage sludge compared with sewage sludge had lower stimulating effects on microbial and enzyme activities.	Emmerling *et al.* (2000); Germany

Table A3 Effects of soil amendment with RO on soil biological properties

Organic amendment type and application rate	Soil type and duration of experiments	Results	References
Biodegradable fraction of MSW+sewage sludge (pots containing same amount of compost or soil+compost)	Clayey and alluvial sandy Pot experiments conducted under natural conditions	Increased growth of fungi and actinomycetes with increasing compost dose. Total aerobic bacteria with increasing compost rate initially increased and then decreased. In sandy soils compost increased cellulolytic activity while was unaffected in clay soils. Growth of nitrite oxidising bacteria was stimulated by compost application.	Pera *et al.* (1983); Italy
Urban waste compost @ 0, 10, 30 and 90 t/ha incorporated to top 25 cm (long term field investigations)	clay loam (Fluventric Xerochrept)	Compost amended plots showed a significant increase in total and humified organic carbon, Pb, Cu and Zn, Enzymatic activities were significantly enhanced by compost additions. Total porosity was greater in composted plots due to larger amount of elongated pores.	Giusquiani *et al.* (1995); Italy
Organic fraction of a MSW @ rate of 6.5, 13, 19.5 and 26 kg/m2 incorporated to top 30 cm soil(field experiments)	Xerric Torrortents	40 months after soil amendment, all amended treatments show increases in OM, available N, water soluble carbohydrates. Treatments with higher amendment rates noticed an increase in enzymatic activity indicating regeneration of the soil from a biochemical aspect.	Garcia *et al.* (1994); Italy

Table A4 Effects of soil amendment with RO on soil physical properties

Organic amendment type	Application rate	Soil type	Crop	Results	Authors
Aerobic sludge; anaerobic sludge; compost of aerobic sludge; organic fraction of urban refuse (40-60%), compost of anaerobic sludge and the organic fraction of urban refuge (20-80%); manure	50 and 150 metric tons/ha on organic carbon basis. Two year field experiments	sandy loam (Typic Psammaquent) Surface applied and ploughed	corn	Increased the total porosity significantly at all sampling times. Modification of pore size distribution were also observed. Stability of soil aggregates increased slightly in treated samples. Best stabilising effect was shown by the anaerobic sludge. Diffrences between the two application rates were generally not significant.	Pagliai *et al.* (1981); Italy
MSW compost; sewage sludge; ovine manure; vermicompost and humic acids	24t/ha/yr; 2.4 t/ha/yr; 100 t/ha/yr % years field experiments	Sandy silty loam (Xerorthernt)		MSW compost, sewage sludge and ovine manure significantly increased organic matter, total humified substances, humic acids,carbohydrates, microbial gums and strictural stability of soil aggregates.MSW compost yoelded the highest result.	Albiach *et al.* (2001); Spain
Mineral fertiliser P & K; Mineral fertiliser N, P & K; Mineral feriliser+low rate of compost (5 Mg/ha of rice straw+cow manure) and mineral fertiliser + high rate of compost (15 Mg/ha of rice straw+cow manure)	5 and 15 Mg/ha Based on 20 years field trials	silty loam gray lowland (Eutric Fluvisol)	Rice and barley double cropping	Fertiliser plus high compost rate increased the most organic C, total N, hydrolyzable carbohydrates, soluble Al, hyphal length and degree of macroaggregation. OM including polysaccharides, active Al and hyphae play an important role together in soil macroaggregation.	Ibrahim and Shindo (1999); Japan
Municipal soil waste compost (field studies for two years)	0, 67 and 134 MT/ha	Fine sandy (Alfichaplaquod)	vegetables	Dry bulk density decreased and water holding capacity of the soil increased however plant available water did not change.	Turner *et al.* (1994); USA
Poultry manure, sewage sludge; barley straw and green alfalfa applied 3 times (field investigations for 2 years)	25 Mg/ha incorporated into 15 cm topsoil	Coarse loamy (Mixed Thermic Haplic Durixeralf)		Soil amendments increased soil respiration rates (139-290%), soil aggregate stability (22-59%), organic carbon (3-25%) and decreased soil bulk density (7-11%). The change in soil physical properties significantly increased cumulative water infiltration rates (18-25%).	Martens and Frankenberger (1992); USA

Table A4 Effects of soil amendment with RO on soil physical properties

Organic amendment type	Application rate	Soil type	Crop	Results	Authors
MSW incorporated or used as mulch or compost layer of 4-5 cm added below the soil surface(glass house and field investigations for two years)	50 t/ha and 100 t/ha	surface soil calcareous browth earth of a silty loam texture		In pot experiments soil amendments either mulch or incorporation raised soil temperature and reduced the water evaporation inearly stages of drying. In field compost addition improved retention of soil water during a normally wet summer, but not during a very dry summer.	Movahedi and Cook (2000); Iran and UK
Sewage sludge, press mud, green manure and farm yard manure (Laboratory experiments)	15.7, 15.7, 15 and 30.2 g of fresh organic matter per 100 g dry soil or equivalent to 827, 1043, 1370 and 542 t/ha of fresh organic matter	Sandy soil (Torripsamment)		Incorporation of all the organic wastes caused an appreciable increase in water retention at a given pressure potential. Only sewage sludge and press mud increased available water. Hydraulic conductivity, penetration coeffcient and cumulative horizontal infiltration decreased markedly with addition of these materials. Maximum decrease in hydraulic conductivity was in case of press mud whereas the maximum decrease in penetration coefficient was in case of farmyard manure. The contact angle having important role in water penetration into media increased more in green manure and farm yard manure.	Kumar *et al.* (1985); India
Mineral fertiliser, Farm yard manure; Compost 1 supplying 100 kg/ha N; Compost 2 supplying 200 kg/ha N; Compost 3 supplying 300 kg/ha N; Surface applied and then ploughed		Calcic Cambisol 2 years field study		Variations were observed for stability of soil aggregates, total porosity, pore size distribution and myccorrhizal infection and aerobic cellulytic microrganism however physical properties (soil aggregates, total porosity and pore size distribution) were not affected.	Guidi *et al.* (1988); Italy
Garbage compost, sewage sludge, cow manure and chicken manure	Various low to high (pot study)	Spodosols having organic pan	Oats and radish	Yields increased progressively with increased compost rate. N uptake increased . Soil pH was unaffected. WHC capacity increased while CEC increased for highest rate. Salts increased for top highest rates.	Hortenstine and Rothwell (1968); USA

Table A4 Effects of soil amendment with RO on soil physical properties

Organic amendment type	Application rate	Soil type	Crop	Results	Authors
Pelletized compost	8, 16, 32 and 64 metric tons/ha. Applied to 0-15 cm depth (pot study)	Sand	Sorghum	All compost rates increased yield. Highest rates produced higher yields. Uptake of all nutrients except Mn increased by compost application. Water retention, OM and CEC increased.	Hortenstine and Rothwell (1973); USA
Municipal refuse compost (laboratory incubation for 7, 90 and 180 days)	15, 30 and 60 t/ha	Clay-sandy soil (Typic Haploxeralf)		Soil structure improved. WHC capacity and alkali-soluble substances increased. Solubility of toxic metals in water and DTPA showed different behaviour	Hernando *et al.* (1989); Spain
Compost from municipal refuse and sewage sludge (field studies for 3 to 4 years)	Compost rates for sorghum from 9 to 183 MT/ha; 0, 9, 18 and 27 MT/ha for bermudagrass and for corn 9 to 448 MT/ha	sorghum was grown on silt loam soils	Forage sorghum, bermudagrass and corn	Positive yield responses were observed at the annual compost application at rates upto 80 MT/ha on bermudagrass, 143 MT/ha on sorghum and 112 MT/ha on corn. Incorporation of compost over 2 years significantly increased mositure holding capacity and decreased bulk density and compression strength of the soil. Soil pH, OM, K, Ca. Mg and Zn levels increased. Zn can accumulate in toxic amounts in the soil if compost were applied at very high rates over few years.	Mays *et al.* (1973); USA
Urban waste compost incorporated to top 25 cm (long term field investigations)	0, 10, 30 and 90 t/ha (Results after 4 years)	clay loam (Fluventric Xerocherpt)	corn	Compost amended plots showed a significant increase in total and humified organic acrbon, Pb, Cu and Zn, Enzymatic activities were significantly enhanced by compost additions. Total porosity was greater in composted plots due to larger amount of elongated pores.	Giusquiani *et al.* (1995); Italy

Table A4 Effects of soil amendment with RO on soil physical properties

Organic amendment type	Application rate	Soil type	Crop	Results	Authors
Anaerobically digested biosolids and composted organic fraction of MSW (field study for 1 year)	0 and 80 Mg dry matter/ha	Degraded semi-arid highly carbonated soil (Rensic Leptosol)		After one year of soil amendment soil structure was slightly improved by small decrease in particle and bulk densities, an increase in water retention accompained by an increase of organic matter. Amorphos iron oxide and the total heavy metals in the soil increased particularly Cu and Zn in the surface level. Zn increased significantly in subsurface level suggesting that Zn migrated in the soil probably because of its affinity with organic matter soluble fractions.	Illera *et al.* (1999); Spain
Compost from green wastes, cow manure, spoiled hay, clay soil and various crop processing residues	0, 22 & 44 Mg/ha	silty clay loam	broccoli	The short term benefits effects of compost were stabilisation of pH and decrease of water infiltration rate. Stabilisation of pH prevented acidification effects due to fertiliser application. High compost rates increased soil EC that may result in N depletion, reduced nutrient cycling and imparied crop growth.	Stamatiadis *et al.* (1999); Greece and USA
Biosolids, biowastes, poultry and food waste compost, composted hog manure solids, mined peat moss and control	45 wet t/ha (1993) 45 dry t/ha (1994, 1995 & 1996) (field experiments for 4 years)	Coarse textured loamy sand (Orthic Brown)		Application of organic wastes for 4 years increased SOM content, decreased soil bulk density, and there was a limited effect on soil CEC.	Zebarth *et al. (* 1999); Canada
Fresh cow manure and MSW compost (laboratory incubation study)	At a rate equivalent to 3% dry matter	Clayey soil (Vertisol)		Soil samples mixed with compost and manure were incubated aerobically, anaerobically and under flooded conditions. Aerobic incubation increased soil density and aggregate stability while anaerobic incubation had no effect. Aerobic incubation increased formation of polysaccharides, polyuronides and humic acids compared to a decrease with time of these components under anaerobic conditions	Avnimelech and Cohen (1988); Israel

Table A4 Effects of soil amendment with RO on soil physical properties

Organic amendment type	Application rate	Soil type	Crop	Results	Authors
Compost, rock dusts and slow release mineral fertiliser (field study)		Yellow earth (Luvic Ferrasol)	Vegetables	Soil that received compost and other materials had higher SOC, microbial biomass, total N and P, exchangeable nutrient cations, water holding capacity and aggregate stability	Wells *et al.* (2000) Australia NSW

Table A5 Effects of soil amendment with RO on soil chemical fertility

Organic amendment t	Application rate	Soil type	Crop	Results	Authors
Leaf compost	125 t/ha rotary tilled 15 cm deep	Loamy and sandy	Tomato	Increase in SOM in sandy soils is less than in fine textured soils due to rapid decomposition. Yield increased on loamy soils than on sandy soils. No of fruit per plant increased with compost amendment. Microbial conversion of organic N to nitrate N is rapid on sandy soils that allow rapid leaching.	Maynard (1999); USA
Sewage sludge+bark compost and MSW	5 mm thick layer of mulch	Calcareous (Typic Udorthents) Medium sandy texture	Apple trees and Grape vine	Increased SOM, Available P, Exch. K. Improved porosity and water retention capacity of the soil. Reduced soil temperature fluctuation, evaporation of soil water and influenced the levels some nutrients.	Pinamonti *et al.* (1995); Pinamonti (1998); Italy
Organic fraction of MSW (greenhouse pot study)	Compost rate @ 10, 20, 30, 40 & 50 t/ha	Ferrallitic soil	Perenial ryegrass	Compost increased dm yield, soil mineral N, plant N uptake proportional to the applied rate.	Iglesias-Jimenez and Alvarez (1993); Spain
Garbage compost, sewage sludge, cow manure and chicken manure	Various low to high (pot study)	Spodosols having organic pan	Oats and radish	Yields increased progressively with increased compost rate. N uptake increased . Soil pH was unaffected. WHC capacity increased while CEC increased for highest rate. Salts increased for top highest rates.	Hortenstine and Rothwell (1968); USA
Pelletized compost	8, 16, 32 and 64 metric tons/ha. Applied to 0-15 cm depth (pot study)	Sand	Sorghum	All compost rates increased yield. Highest rates produced higher yields. Uptake of all nutrients except Mn increased by compost application. Water retention, OM and CEC increased.	Hortenstine and Rothwell (1973); USA
Compost+ N fertiliser compost ; and vermicompost (field plots)	3 Mg/ha; 3, 7.5 and 30 Mg/ha; 3, 7.5 and 30 Mg/ha incorporated into soil	sandy loam (Argixerferoll)	Broccoli	Increasing applications of composts alone tended to increase yield and N accumulation, yet decreased all measures of N use efficiency. Higher than 7.5 Mg/ha rate was significant for broccoli yield. When used with fertiliser N, the lower applications of compost significantly improved crop responses.	Buchanan and Gliessman (1991); USA
Biosolids; composted biowastes including MSW and peat (3 yearield trials)	45 wet t/ha (1993) and 45 dry t/ha	coarse textured loamy sand (Orthic Brown) Chernozenic soils	carrot and chard	Yield of chard and carrot increased organic treatments plus fertilisers relative to only mineral fertilisers. Leaf N, P, Zn and Cu concentrations of both crops were usually elevated but not toxic values for treatments containing high concentration of respective nutrients. Extractable P, Zn and Cu increased in the surface 15 cm of soil as compared to the control.	Neilsen *et al.* (1998); Canada
Sewage sludge compost (2 year field experiments)	0, 37 and 74 MT/ha total applied for 2 years	sandy loam mixed calcareous thermic (Typic Xerothents)	Onion, lttuce, snapdragon, turfgrass	Yields of onion, turf and lettuce increased while snapdragon yield was not affected. 74 dry MT/ha rate compost amendment increased OM, primary nutrients, soluble salts and heavy metals and lowered pH.	Bevaqua and Mellano (1993); USA

Table A5 Effects of soil amendment with RO on soil chemical fertility

Organic amendment t	Application rate	Soil type	Crop	Results	Authors
Urban waste before and after composting (laboratory experiments)	30, 60, 120 and 180 t/ha	Calcareous (Calciorthid) having high levels of Ca	Ryegrass	The addition of fresh urban waste depressed ryegrass yield, which disappeared with time as this waste matured in the soil. Composted waste did not show any depressive effects. Yields were significantly higher for higher doses of composted urban waste.Plants grown in amended soil had higher concentration of Fe, M and Zn.	Garcia et al. 1991; Spain
Non composted MSW+poultry litter; Noncomposted MSW+NH4NO3 Two application in fall and spring		Sandy loam (Typic Hapludults) Field and greenhouse experiments	Maize	Soil P, K, Ca and Mg increased in the top 0-15 cm by 3 or 4 times. After two applications Cu, Zn and Pb increased two times while Co and Cr decreased.	Press *et al* . (1996); USA
MSW compost; sewage sludge; ovine manure; vermicompost and Humic acids	24t/ha/yr; 2.4 t/ha/yr; 100 t/ha/yr % years field experiments	Sandy silty loam (Xerorthernt)		MSW compost, sewage sludge and ovine manure significantly increased organic matter, total humified subtances, humic acids,carbohydrates, microbial gums and structural stability of soil aggregates. MSW compost had the greatest effect.	Albiach. (2001); Spain
Mineral fertiliser P & K; Mineral fertiliser N, P & K; Mineral feriliser+low rate of compost (5 Mg/ha of rice straw+cow	5 and 15 Mg/ha Based on 20 years field trials	silty loam gray lowland (Eutric Fluvisol)	Rice and barley double cropping	Feriliser plus high compost rate increased the most orgainc C, total N, hydrlyzable carbohydrates, soluble Al, hyphal length and degree of macroaggregation. OM including polysaccharides, active Al and hyphae play an important role together in soil macroaggregation.	Ibrahim and Shindo (1999); Japan
Municipal refuse compost (laboratory incubation for 7, 90 and 180 days)	15, 30 and 60 t/ha	Clay-sandy soil (Typic Haploxeralf)		Soil structure improved. Water holding capacity and alkali-soluble substances increased. Solubility of toxic metals in water and DTPA showed different behaviour	Hernando *et al.* (1989); Spain
Urban waste compost incorporated to top 25 cm (long term field investigations)	0, 10, 30 and 90 t/ha (Results after 4 years)	clay loam (Fluventric Xerocherpt)	corn	Compost amended plots showed a significant increase in total and humified organic carbon, Pb, Cu and Zn, Enzymatic activities were significantly enhanced by compost additions. Total porosity was greater in composted plots due to larger amount of elongated pores.	Giusquiani *et al* . (1995); Italy
Compost of urban waste (results of 19 years demonstration research trials)	Various			Data show that the beneficial effect of compost application include sustained higher crop yields, a more favourable soil pH, increased organic matter and CEC and enhanced supplies of primary and secondary plant nutrients. While heavy metals increased in surface soil but there was no downward movement of these metals	Anonymous (1993); USA

Table A5 Effects of soil amendment with RO on soil chemical fertility

Organic amendment t	Application rate	Soil type	Crop	Results	Authors
Anaerobically digested biosolids and composted organic fraction of MSW (field study for 1 year)	0 and 80 Mg dry matter/ha	Degraded semi-arid highly carbonated soil (Rensic Leptosol)		After one year of soil amendment soil structure was slightly improved by small decrease in particle and bulk densities, an increase in water retention accompained by an increase of organic matter. Amorphos iron oxide and the total heavy metals in the soil increased particularly Cu and Zn in the surface level. Zn increased significantly in subsurface level suggesting that Zn migrated in the soil probably because of its affinity with organic matter soluble fractions.	Illera *et al.* (1999); Spain
Organic fraction of a MSW (field experiments)	6.5, 13, 19.5 and 26 kg/m2 incorporated to top 30 cm of the soil	Xerric Torrortents		40 months after soil amendment, all amended treatments show increases in OM, available N, water soluble carbohydrates. Treatments with higher amendment rates increased enzymatic activity indicating a biochemical regeneration of the soil.	Garcia *et al.* (1994); Italy
Compost from green wastes, cow manure, spoiled hay, clay soil and various crop processing residues	0, 22 & 44 Mg/ha	silty clay loam	broccoli	The short term benefits effects of compost were stabilisation of pH and decrease of water infiltration rate. Stabilisation of pH prevented acidification effects due to fertiliser application. High compost rates increased soil EC that may result in N depletion, reduced nutrient cycling and impaired crop growth.	Stamatiadis *et al.* (1999); Greece and USA
Compost, rock dusts and slow release mineral fertiliser (field study)		Yellow earth (Luvic Ferrasol)	Vegetables	Soil that received compost and other materials had higher SOC, micrbial biomass, total N and P, exchangeable nutrient cations, water holding capacity and aggregate stability	Wells *et al.* (2000); NSW Australia

Table A6

Predicting equilibrium soil organic carbon levels under different climatic conditions for a range of soil texture using CENTURY

The CENTURY CARBON MODEL (Metherell et al.1993)

In this model, soil organic carbon (SOC) is divided into three pools with different turn over rates (lability), each in turn modified by soil texture,

Active pool (1-5 years)
Slow pool (20-50 years)
Passive pool (400-2000 years)

Soil organic carbon level is a function of a number of factors including soil types (mainly soil texture), precipitation, temperature, vegetation and management. For the CENTURY MODEL, inputs requirements are

1. initial soc level
2. monthly rainfall
3. monthly minimum and maximum temperatures
4. soil texture

To model the equilibrium soil organic carbon level for a particular location (given climatic and soil texture), it was assumed that a cropping soil with an initial soc level of 1 % is converted to pasture and the changes in soc was then modelled for 2000 years. Three soils were chosen to cover a range of soil texture, namely a sandy soil, a clay loam and a clay (Table A1). Soil organic carbon changes for the three soils were modelled for three sites in New South Wales (climatic environment) , namely Sydney, Cowra and Wagga Wagga

Table A1 – Texture composition of the three soils used for soil organic carbon modelling using CENTURY

Soil (texture)	% clay	% silt	% sand
Sandy soil (Yellow earth, Somersby)	15	8	77
Loamy soil (Red earth, Wagga Wagga)	29	13	58
Clay soil (Vertisol, Walgett)	61	17	22

Reference

Metherell, A.K., Harding, L.A., Cole, C.V. and Parton, W.J. (1993). CENTURY – Soil Organic Matter Model Environment, Technical Documentation Agroecosystem Version 4.0, Great Plain System Research Unit, Technical Report No. 4, USDA-ARS, Fort Collins, Colorado, USA