Scoping Paper: Soil Organic Carbon Sequestration Potential for Agriculture in NSW

K Y Chan, A Cowie, G Kelly, Bhupinderpal Singh, P Slavich

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K Y Chan, A Cowie, G Kelly, Bhupinderpal Singh, P Slavich

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Executive Summary

Soil Organic Carbon (SOC) refers to the carbon in soils associated with the products of living organisms. It is a heterogenous mixture of simple and complex organic carbon compounds which can be divided into different pools which serve different functions to soil ecosystems.

SOC is of fundamental importance to soil health/fertility and therefore to sustainable agriculture as it affects all three aspects of soil fertility, namely chemical, physical and biological fertility.

SOC is part of the global C cycle and the global SOC pool (1580 Gt) is twice as large as that in the atmosphere and nearly three times that of the vegetation biomass carbon pool. Soil organic carbon sequestration refers to the storage of carbon in soil and is being considered as a strategy for mitigating climate change. Globally as well as for some individual countries, it has been estimated that SOC sequestration has the potential to mitigate 5-14% of total annual greenhouse gas emissions for the next 50-100 years. However, whether this potential is achieved depends on economic, social and political factors.

Based on limited local data and overseas experience, considerable SOC sequestration potential exists in NSW agricultural land. The highest potential exists in pasture land in the higher rainfall regions (>450 mm), both as permanent pastures or as ley pasture in the cropping zone. Considerable increases can be achieved by pasture improvement and improved management practices.

Significant SOC potential also exists in the low rainfall rangelands which comprises nearly 50% of NSW. Much of the rangelands are in degraded state and considerable total SOC sequestration can be achieved for a small rate of sequestration per hectare. Promotion of conservation tillage practices (particularly no-tillage) is important to halt further carbon losses from cropping soils (emission avoidance). Currently, there is only a 35% adoption rate of conservation tillage techniques in NSW. In addition, SOC can be sequestered by adopting new land conversion and soil amelioration options such as bioenergy crops from perennial vegetation, recycling organics including biochars, and by ameliorating sodic and acid soils. As a rough estimate, total SOC sequestration potential from pasture land, cropping land and rangelands amounts to 4.9 Mt C/yr (18 Mt CO_2e/yr), which is equivalent to 11% of the total GHG emission from NSW in 2005.

Many of the management practices that are effective in increasing SOC in agricultural soils also improve productivity and profitability, conserve the resource base and protect the environment.

In order to support a role for soil organic carbon in emissions trading, there is an urgent need to resolve several key research issues, namely developing low cost methods of accounting for soil carbon; quantifying net carbon sequestration under different management practices for different soil types, climates and agricultural systems by supporting existing long term cropping rotation trial sites and the establishment of new ones where appropriate; quantifying interactions of SOC sequestration with soil emissions of other GHG, namely N_2O and CH_4 and developing soil carbon models that can account for locally relevant agricultural management practices.

It is important to resolve outstanding research questions as a matter of urgency, to remove this barrier to inclusion of soil carbon in emissions trading.

1. Introduction

Soil Organic Carbon (SOC) refers to the carbon in soils associated with the products of living organisms. It is a heterogenous mixture of simple and complex organic carbon compounds which can be divided into different pools dependent on their ease of decomposition and functions in soil. The use of soil to sequester carbon needs to consider at least 3 significant soil carbon pools.

These carbon pools are the labile, less labile (recalcitrant) and inert fractions. The labile soil carbon pool consists mainly of soil organisms, polysaccharides, celluloses and hemi-celluloses with a half life in soils varying from weeks to months. The recalcitrant pool consists of lignins, lipid polymers, suberins, resins, fats, and waxes with half lives varying from years to decades. This pool also contains humified products formed by biological transformation of carbon compounds. The inert pool consists of charcoal and pyrolysed carbon with half lives of centuries to millennia.

The amount of soil carbon in these different fractions depends on the quality of the organic matter being added to the soil as well as their decomposition products through the biological process of humification. Humified soil carbon products have highly aromatic structures such as poly-phenols and hence very slow decomposition rates. Their formation is constrained by low levels of N, P and S (Lal, 2008). They also have much lower C/N ratios than labile SOM due to both loss of carbon and incorporation of soil nitrogen.

Soil organic carbon is of fundamental importance to soil health as it affects all three aspects of soil fertility, namely chemical, physical and biological fertility. The activity of living organisms in soil is dependent on regular inputs of organic matter.

Soil Organic Carbon (SOC) is part of the global C cycle and the global SOC pool (1580 Gt) is twice as large as that in the atmosphere and nearly three times that of the vegetation biomass carbon pool. Soil organic carbon sequestration refers to the storage of carbon in soil and is being considered as a strategy for mitigating climate change.

2. Soil organic carbon sequestration and GHG mitigation potential – processes and factors

Soil organic carbon levels in ecosystems are controlled by a range of factors, namely climate, soil, vegetation and time and can reach an equilibrium level under specific environmental conditions (environmental equilibrium). Over time, change in the storage of SOC is controlled by the balance between carbon inputs and losses (removal through mineralisation to carbon dioxide, and erosion). The difference in SOC between the environmental equilibrium levels and the current depleted level is the SOC sequestration potential, that is, the potential C sink, because theoretically this quantity can be restored to the soil.

SOC levels in soils are very dependent on management practices that affect the inputs as well as removal of carbon materials, namely net primary production, quality of organic residues, residue management (eg burning, incorporation), soil management (eg tillage) and livestock management. In certain cases, additional SOC sequestration in excess of natural equilibrium level can also occur due to increased productivity as a result of removal of inherent soil constraints limiting plant growth. An Australian example is the documented SOC increases in pasture soils as a result of phosphorus fertiliser application (Russell and Williams 1982). In these cases, the equilibrium SOC level of natural ecosystems can be exceeded under agriculture.

Smith *et al.* (2008) reviewed studies to estimate the average annual mitigation potential, accounting for changes in emissions of all GHGs, of agricultural practices in different climatic zones (warm-dry, warm-moist, cool-dry, cool-moist). Best practice cropping, incorporating improved agronomic, nutrient, tillage and residue management was estimated to have an average annual GHG mitigation potential of 0.29 t C (or 1.07 t CO_2-eq.) ha^{-1} yr^{-1} in warm-dry climates and 0.63 t C (or 2.32 t CO_2-eq.) ha^{-1} yr^{-1} in warm-moist climates[1]. It should be noted that the range in greenhouse gas mitigation from adoption of the practices is very large (-0.25 to 0.88 and 0.26 to 1.30 t C ha^{-1} yr^{-1} for warm-dry and warm-moist climates, respectively). This range of observed values is probably due to different starting SOC levels, time periods and site productivity factors. The warm-dry climate estimates would represent potential GHG mitigation rates for the NSW inland cropping regions whilst the warm-moist climate estimates would represent potentials for coastal cropping areas of NSW. Note the proportion of total crop production from coastal regions is likely to increase as inland areas become proportionally drier.

Smith *et al*. (2008) estimated land use change from cropping to regeneration of native vegetation could have an average annual GHG mitigation potential of 3.93 and 5.36 t CO_2-eq. ha^{-1} yr^{-1} in warm-dry and warm-moist climatic areas. The highest annual greenhouse gas mitigation potential of 70.18 t CO_2-eq. ha^{-1} yr^{-1} was associated with restoration of organic soils (peat soils) by raising the watertable. Hence land use change to forestry or wetlands in coastal regions may have greater greenhouse gas mitigation potential than adoption of best practice cropping. However, this would result in the loss of secure food producing areas.

Table 1 lists the management practices that can increase SOC sequestration in agricultural systems and the SOC sequestration rates that have been reported in the literature. A number of salient features can be drawn from Table 1

- Many of the practices that are effective in increasing SOC are closely related to sustainable development, many of these are being promoted as Best Management Practice (BMP) by NSW DPI such as conservation tillage, pasture management, increasing use of perennial pasture; agro-forestry etc. Hence, soil carbon sequestration can bring about co-benefits which can help to achieve wise use of natural resources and sustainable development in the rural sector (WIN-WIN option);
- Most of the data of SOC sequestration rates is from overseas studies which does not necessarily translate to Australian conditions and soils;

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[1] Note: all figures in this report are in tonnes of carbon. These can be converted to CO^2e by multiplying by 3.67.

- SOC sequestration has a finite capacity. Soil carbon stock may increase only until the environmental equilibrium level is achieved, possibly in 50-100 years of improved management practice.
- The environmental equilibrium is likely to be lower than the current level under a hotter-drier climate future.
- Most of the soil carbon sequestered is not permanent and can be lost if the improved management practice is stopped. The use of biochar and soil amelioration such as gypsum application could be an exception to this.
- The effect of the same management practice on SOC is expected to be different in different locations with different soil types and climatic regimes (rainfall and temperature). Hence, regional methods of assessment will be necessary.

Table 1. Literature review of management practices and land use practices that can increase soil organic carbon and observed SOC sequestration rates associated with these practices

Management Category	**Management Practices**	**Carbon Sequestration rates (t C/ha/yr)**	**Reference**
Crop management	Soil fertility enhancement	0.05-0.15	
	Better rotation	0.10-0.30	
	Erosion control	?	Lal *et al*. 2003
	Irrigation	0.05-0.15	
	Fallow elimination	0.10-0.30	
	Precision agriculture	?	
Conservation tillage	Stubble retention		
	Reduced tillage	0.24-0.40	Lal *et al.* 2003
	No-tillage		
Pasture management	Fertilizer management	0.30	
	Grazing management	0.35	
	Earthworm introduction	2.35	
	Irrigation	0.11	Conant *et al.* 2001
	Improved grass species	3.04	
	Introduction of legumes	0.75	
	Average	0.55	
	Sown pasture	0.50	Gifford *et al.* 1992*
	Introduction of perennial pastures	?	
Organic amendments	Animal manure	0.1-0.6	Jarecki and Lal, 2003
	Green manure	?	
	Biochar	?	
	Biosolids	1.0	Brown 2004
Land conversion	Degraded cropland to pasture	0.8-1.1 ?	
	Buffer strips	0.98	Grogan and Matthews, 2001
	Bioenergy crop	?	
	Mine rehabilitation		
Soil improvement	Sodic soil	?	
	Acid soil	?	

* Australian data; '?' indicates lack of information

3. Global SOC sequestration potential

Worldwide, clearing and subsequent management practices on agricultural land have resulted in significant loss of soil carbon. Globally this has been estimated to be 78± 12 Gt C (this is equivalent to 29 % of total CO_2-C emission due to fossil fuel combustion of 270± 30 Gt (Lal *et al.* 2007)).

Various attempts have been made to estimate the potential of SOC sequestration globally as well as in different countries based on different scenarios as a result of changing management practices and land use (Table 2).

Table 2. Estimates of potential SOC sequestration globally and in selected countries as compared to total carbon emissions

	Total C emission/yr	**C sequestration rate due to improved management, Gt/yr**		**% of total C emission**	**Reference**
		Current	Potential		
Global -(1)	9.1 Gt*	0.4	0.44-0.88	5-10 %**	Paustian *et al.* (2004)
Global -(2)	13.4 Gt	-	1.50-1.63†	11-12%	Smith et al. (2007)
USA	2.00 Gt*	0.017	0.288	14 %	Lal *et al.* (2003)
Europe	1236 Mt	˜0.0	104	8.3 %	Smith *et al.* (2000)
Australia	154 Mt*	?	?	?	AGO (2007)

* total GHG emission; ** for up to next 50 years; †by 2030

All the evidence points to substantial potential of SOC sequestration to mitigate climate change. Overall this potential contribution is equivalent to 5-14% of total annual GHG emissions and is expected to last for the next 50-100 years. Furthermore, according to the latest IPCC estimates, soil carbon sequestration globally can contribute to 89% of the total technical mitigation potential for agriculture whereas mitigation of soil CH_4 and N_2O emissions account for only 9% and 2% respectively (Smith *et al.* 2007). This further indicates the significant role that SOC sequestration can play in mitigating climate change.

Globally around 90% of the technical GHG mitigation potential from agriculture will arise from improved management of crop lands, grazing lands, organic soils and degraded soils. Further small contributions can be made from (in order of significance) improved management of rice, livestock, bioenergy crops, irrigation water, land use change, agroforestry and manure management (Smith *et al.* 2008). Approximately 50% of the technical GHG mitigation potential from agriculture occurs in Asia and South America.

However, this potential has to be critically evaluated based on the following additional information.

1. *Technical potential vs actual potential*
All the potential estimates in Table 2 refer to the technical potential. In reality only a proportion of this total SOC sequestration potential can be realised dependent on a range of economical, social and political factors. In the case of the US, it has been estimated the current SOC sequestration rate is the result of a number of Government Incentive Schemes. For example, the Conservation Reserve Program is a mere 0.017 Gt C/yr which is only 6 % of the technical potential. Researchers in Europe (Smith *et al.* 2005)) highlight that without incentives for carbon sequestration in the future, cropland carbon sequestration under Article 3.4 of the Kyoto Protocol will not be an option as a mitigation strategy in EU-15.

2. Strong emphasis based on land conversion scenarios
The various estimates presented in Table 2 highlight the importance of land conversion in sequestering SOC. For instance, for the estimates for Europe, land conversion involving bioenergy crops and woodland regeneration (from surplus cropland) accounts for 63 % of the potential SOC sequestration (Smith *et al.* (2000)). Similarly, Lal *et al.* (2003) estimated that for the U.S., 32 % of the potential SOC sequestration will be derived from a combination of land conversion and soil restoration. In both cases, land conversion and the associated SOC sequestration will not take place without new policy incentives.

4. Australian situation

Australia is a very old continent and many of the soils including those which have been intensively used for cropping are highly weathered and are often characterised by physical and chemical constraints and low SOC levels.

Soil carbon change due to land use change is included in Australia's national GHG inventory (AGO 2007a). The emissions due to land clearing include a component for loss in soil carbon stock. However, for land where there is no change in land use there is assumed to be no change in soil carbon stock. The contribution of soil carbon change in agricultural systems to the GHG balance in Australia is not clear.

However, similar to the rest of the world, it has been estimated that 10-60% of the SOC has been lost in Australian cropping soils (Dalal and Chan 2001). Therefore SOC levels of many cropping soils are expected to be substantially lower than pre-clearing levels. As a rough estimate, based on a total arable soil area of 41 Mha (20 Mha under cropping and 21 Mha under ley pasture in rotation in the mixed farming) and assuming a soil carbon stock of 30-60 t C t/ha (over 30 cm depth), the total historical loss in SOC (and therefore theoretical SOC sequestration potential) is 646 Mt C. This can be compared to an earlier estimate of 250 Mt C by Russel and Williams (1982) which was based on 0-10 cm soil depth. Assuming a 50 year time span, it is equivalent to an emission rate of 12.9 Mt C/yr or 8.4% of total GHG emissions for Australia (based on 2005 data, AGO, 2007a)

5. NSW situation

5.1 SOC sequestration potential

Little information is available on the net balance of SOC and as such it has not been included in the NSW GHG inventory (AGO, 2007b). However, there are data available showing positive and negative SOC changes in response to a range of agronomic and soil management practices.

Agriculture is the dominant land use system in NSW (Table 3), accounting for 76% of the State (DECC 2006). Of the total agricultural land, pasture for grazing (69.8%) is the largest land use, followed by cropping (7.9%).

Table 3: Areas of cropping and different pastures in NSW

Land use	Area (Mha)	Comments
Cropping*	7.7	
Sown pasture†	43.8	Part of this is ley pasture in rotation with cropping
Un-improved native pasture†	29.3	Much of this is rangeland in Western Division
Fertilised native pasture†	1.4	In high rainfall areas, e.g. Tablelands

* ABS (2006); † Hill and Donald (1998)

5.2 Opportunities for different farming systems/management practices/landuse

5.2.1 Existing agricultural landuse

Cropping soils:

Conservation farming practices including no-tillage and stubble retention are known to minimise soil carbon losses from agricultural soils. Results from long term trials in Wagga Wagga have shown, over a 20 year period, the soil under traditional practice (stubble burnt and traditional tillage) was losing carbon at a rate of 400 kg/ha/year compared to conservation tillage (no-till and stubble retained) (Heenan *et al.* 2003). However, while effective in reducing SOC losses, combined no-tillage and stubble retention did not lead to detectable increases in SOC over the same period. So it clearly shows that under conventional practices of multiple cultivation and stubble burning, cropping soils can be carbon sources.

Greenhouse gas accounting for soil carbon in agriculture under the Kyoto Protocol is based on the rate of change in carbon stock. Therefore, if conventional practice causes a decline and the new practice reduces the rate of loss, credit can be earned. This is a real reduction in emissions that could be counted under an emissions trading scheme. Note, however, that Australia has elected not to count cropland management for first commitment period 2008-2012.

A study from northern NSW (Young, unpublished) suggests that the potential of net carbon sequestration under no-till management is more limited under NSW climatic conditions than some other parts of the world. Countries such as northern America have colder winters and are likely to reduce the rate of SOC mineralisation (Chan *et al.* 2003). Nevertheless, adoption of conservation farming is still essential to reduce/remove soil carbon loss under cropping in Australia.

It should be noted that the adoption of conservation tillage in NSW is the lowest of all Australian States. In 2007, the adoption rate of no-till in NSW was only 35% compared to 90% in Western Australia (Flower *et al.* 2008). The reasons for this are not well understood but it is likely that it is a range of factors including cultural reasons, a lack of suitable machinery and of the ability to purchase the machinery, and poorer yield resulting from poor early growth under no-tillage (in some parts of NSW).

From the latest data (GRDC, in press), it has been estimated that in NSW, about 1.5 Mha of cropping soils was no-tilled with the rest still being reduced or multiple-tilled in 2002. Assuming a carbon loss rate of 200 kg C/ha/yr, the annual carbon emissions from NSW cropping soils that are still being tilled is 1.04 Mt C/yr. This compares to 4 Mt C/yr loss Australia wide estimated by Swift (2001).

Pasture soils:

(i) Permanent pastures in higher rainfall areas

In Australia, research has demonstrated that pasture improvement (such as sown pasture or fertiliser application) can lead to significant increases in SOC sequestration (500 kg C/ha/yr, Gifford *et al.* 1992) compared to unimproved pasture. Long term trials in Australia have shown that this rate of SOC increase can be maintained for at least 40 years as a result of pasture improvement (Russell and Williams, 1960). Other trials on improved pasture management treatments such as phosphorus and lime application have led to soil carbon sequestration at rates of 388-464 kg/ha/year between 1992 and 2005. It has been estimated that on the Southern Tablelands, many farmers still have 20-40% of their farms under unimproved native pasture and these pastures have the potential of substantial increases in SOC for many years if subjected to improved management practices. However, this potential needs to be assessed against other environmental trade-offs such as possible loss in biodiversity, or increase of other GHG emissions.

In addition, there are other pasture management practices that are likely to affect SOC, namely grazing management and use of other pasture species. Regarding the latter, there is a recent move to increase the proportion of perennial pastures with deeper root systems in the landscape for the control of dryland salinity. However, the effects of these management practices on SOC sequestration are not known. There is also another potential environmental trade-off in terms of catchment water yield.

With funding from the NSW Climate Action Grant Program, a project is currently underway to quantify the SOC sequestration of a range of pasture management practices in southern NSW including nutrient management, grazing management, pasture types (native, annual and perennial) and pasture cropping systems.

(ii) Rangelands

NSW has the highest area of unimproved native pasture in Australia (29.3 Mha, 77% of Australian total, Hill and Donald (1990)). Most of this is located in the low rainfall areas of the state (the rangelands).

Inherent productivity and soil carbon levels are low in the rangelands. However, because of the large area involved, small increases in soil carbon level due to change in management practices will result in considerable sequestered soil carbon. It has been estimated that there are 48 Gt carbon in the whole Australian rangelands, thus an increase in SOC of 1% of the existing level over the whole rangeland is equivalent to 480 Mt carbon. In addition, just as a rough guide, assuming a SOC sequestration rate of 100 kg/ha/year (US data, Follett *et al.*1998) over 20 Mha of the Western Division of NSW, would result in a SOC sequestration rate of 2.0 Mt C/year (7.3 Mt CO_2 eq/year). This represents considerable mitigation potential, although this should be tempered by the fact that varying management practices costs much the same per hectare whether it is in the western division or a high rainfall area, but the economic (and carbon sequestration) returns are much lower in the Western Division. This means that there may be limited opportunity for land managers to derive a return from this activity.

Previous research has demonstrated that accelerated soil erosion, reduction in soil hydraulic conductivity and loss of perennial pastures which characterised land degradation in the rangelands are invariably accompanied by significant losses in surface SOC (e.g. Greene and Tongway 1989). According to Hill *et al.* (2002), the major sink potential of the rangelands lies in the reduction and reversal of soil degradation and the implementation of improved management regimes. The effect of grazing management on soil carbon dynamics particularly its interaction with climate change, climate variability, and drought in rangeland soils is not well understood. Research is needed to quantify the effect of management practices on soil carbon sequestration in rangelands (Hill *et al*. 2002).

(iii) Ley pasture

Unlike many other parts of the world, continuous cropping on the same piece of land is not common in Australia. Most dryland cropping is undertaken in rotation with pasture. Traditionally, the pasture phase between cropping helps to restore chemical and physical fertility of the soil and this is often accompanied by SOC increases. The extent of SOC increase is dependent on management factors such as the duration of the pasture phase, pasture type, grazing and nutrient management during the cropping phase. Opportunities exist to increase the SOC within the ley-crop farming systems by improving management of pasture and crop components as well as during the transition phase.

The results in Figure 1 demonstrate the usefulness of using a modelling approach to design more optimal ley-crop systems in term of SOC sequestration.

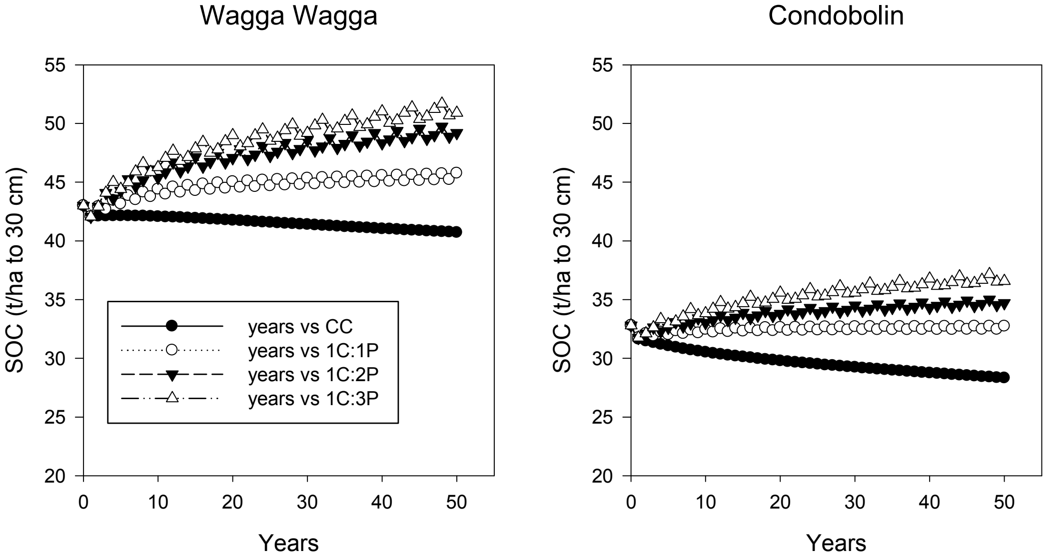

Fig. 1 Modelling of SOC changes under different crop/pasture duration at two contrasting locations in NSW – design of crop pasture rotation (Liu and Chan, =unpublished data). CC = continuous cropping; C:P = crop : pasture ratio.

Under continuous cropping, SOC declines at both locations, with Condobolin declining at twice the rate as that of Wagga Wagga. Wagga Wagga, enjoys a higher rainfall and therefore higher crop and pasture yield, and as such a smaller decline in SOC is predicted under continuous cropping. But a 1:1 crop pasture rotation results in an increase in SOC which increases at faster rates with increasing pasture frequency. For Condobolin, the drier location, continuous cropping results in a much higher rate of SOC loss and it requires at least a 1:2 crop:pasture rotation to result in net SOC sequestration.

5.2.2 Soil improvement and amelioration

(i) Organic amendments

Recycled organics can play a positive role in direct addition of carbon to the soil, reversing soil organic matter decline. Recycled organics comprise of biosolids, composts, biochar, manures and mulches. These products are imported to the site for application and hence are a redistribution of organic resources produced at other sites. Long term experiments in Europe have shown that soils treated with organic amendments have between 20%-100% more SOC than soils treated with inorganic fertilisers (Lal, 2008).

Potential and availability of recycled organics

Sydney Water generated 195,500 product tonnes of biosolids in 2006-2007. All of the biosolids is being re-used, principally in agriculture and composting. Production volumes have been steady, although with increasing levels of treatment and an increasing population it is likely that the available product will also increase.

During 2005/06, the Hunter Water Corporation produced 6152 dry solid tonnes of dewatered biosolids, of which 100% was beneficially re-used. The past 5 years have shown a steady increase in the volume of biosolids produced. In 2005-06 90.93% of biosolids were reused in mine site rehabilitation, 8.82% in agriculture, and the remainder was used in municipal composting and landscaping (Hunter Water Corp, 2006).

In NSW, over 600,000 tonnes of garden organics, such as grass clippings, prunings and other vegetation, are collected from households and municipal areas each year and composted to produce about 0.3 m tonne/yr of composted garden organics (DEC 2004).

Forestry residues are also a potential source of organic amendment although the collection of biomass from native forests is currently precluded by legislation. There are some thinnings from relatively young hardwood plantations but the most productive area for sourcing forest biomass is the softwood estate. The harvesting of plantations results in significant volumes of residue material which has historically been windrowed and burnt on-site. Changing technologies, developing markets and government initiatives provide new opportunities for residue management which will be tested through a competitive allocation process.

Forests NSW recently put out to tender the “Residue” biomass from the Macquarie region softwood estate (FNSW, 2008). The annual volume on offer through this call for Expressions of Interest is up to 150,000 green t/ha per annum of forest residue.

Current NSW DPI research on recycled organics.

Under a Climate Action Grant, NSW DPI is conducting research that aims to (i) determine the total and different fractions of soil organic matter before and sequentially after amendment with recycled organics; (ii) assess the efficacy of different recycled organics in increasing and maintaining soil carbon stocks over time; and (iii) maximise the role of recycled organics in the long term enhancement of soil carbon.

This study focuses on storage by direct addition of carbon, from recycled organics (biosolids, composted garden organics, municipal solid waste compost) to soil, and determining the recalcitrant and labile fractions of the soil carbon pool using mid-infrared spectroscopy (MIR) technique. Labile fractions improve soil qualities and plant growth, while inert pools are most relevant for long term carbon sequestration.

Preliminary results suggest that SOC in the 0-30 cm layer is responding to organic additions, including increases in the recalcitrant soil carbon fraction (Kelly and Cowie 2008). Biosolids application has increased the productivity of plantation trees which has in turn also added more carbon to the soil as litter.

Application of organic amendments may be particularly important in maintaining SOC on reforested sites. Under conventional practice, soil carbon is likely to decrease initially, as a result of a decline in pasture litter inputs in the early phase of plantation establishment, and then increase as litter input from the forest is added to the system. As the plantation grows, soil carbon is replenished from litter fall and root turnover, usually restoring soil carbon to original stock within 30 years (Paul *et al.* 2002). However, biosolids can maintain soil carbon even after the disturbance of establishment (Kelly 2005).

Currently agriculture accounts for only 4% of the market for green garden organic compost products. Research is currently underway at NSW DPI's Centre for Recycled Organics in Agriculture (CROA) aiming at quantifying the benefits of using a range of recycled organics in agriculture. An increase in SOC of 13 t C/ha was measured in a vegetable trial using garden organic compost in CROA (Chan *et al.* 2007). Trials of recycled organics for mine site rehabilitation with plantation trees have been undertaken (Kelly 2005, 2006, 2007) and their benefits quantified and compared to mineral fertiliser. The recycled organics provide superior outcomes to mineral fertiliser. As a result mine sites are increasing the use of theses products in the rehabilitation process.

Biochar is an organic material produced by low temperature pyrolysis of biomass materials. Carbon in biochar is likely to be present in a more recalcitrant form than that in compost products and so should be more stable when applied to soils. Therefore biochar can be of higher carbon sequestration value (on per unit mass basis of the product). The potential value of biochar to agriculture and climate change mitigation has not been quantified for the range of farming systems/soil types/climatic regimes of NSW. Long term field research is required to quantify its agronomic values (nutrient, crop yield and improvement in soil properties) as well as the carbon sequestration value. NSW DPI is leading the rest of Australia in biochar research and has a number of field trials and laboratory experiments underway with promising early results in terms of both carbon sequestration and agronomic benefits.

Besides the benefit of increasing soil carbon, organic amendements can reduce the need for chemical fertiliser. The manufacture of nitrogen fertiliser is a particularly greenhouse-intensive process, consuming natural gas or other hydrocarbon sources to supply the hydrocarbon feedstock and to meet energy requirements of the process. Emissions have been calculated to exceed 5kg CO_2 per kg nitrogen (Wood and Cowie 2004). Thus, reduced need for manufacture of nitrogen fertiliser will reduce Australia's industrial GHG emissions.

(ii) Amelioration of sodic and acid soils

Plant productivity is often low on sodic and acidified soils. Hence, carbon inputs to the soil are also low. In 1998 ARMCANZ (now Primary Industries Ministerial Council) identified sodicity and acidity as the two major soil constraints adversely affecting sustainable development of agriculture in Australia (Agriculture and Resource Management Council of Australia and New Zealand 1998). Sodic soils occupy about one third of Australia, with 134 Mha in the cropping and improved pasture zone where rainfall is over 300 mm (Hamblin 2000). It has also been estimated that in NSW, the proportion of sodic soils is estimated to be 47% (McKenzie et al. 1993).

Sodicity not only limits the potential productivity of crops and pastures, it also presents environmental and management problems in agriculture production (on site as well as off site) such as dryland salinity, sedimentation, poor water use efficiency and poor water quality.

Using gypsum to ameliorate sodicity is well established and improvements in crop and pasture yield as well as soil properties have been demonstrated in many soil types, climatic zones and cropping systems of NSW. However, there is little information on the long term SOC sequestration as a result of sodic and acidic soil amelioration. The ARMCANZ report also concluded that soil conditioners are not being used enough to redress these problems.

5.2.3 Impact of reforestation on soil carbon

Conversion of cropland to forest is likely to increase soil carbon; from their meta-analysis of published literature, Guo and Gifford (2002) concluded that, on average, reforestation of cropland increases soil carbon stock by 18%–20%.

Conversion from pasture to forest increases soil carbon in some circumstances, and decreases it in others. Reforestation is likely to initially decrease soil carbon stock, as a result of disturbance during site preparation, and low rate of root litter inputs in the early phase of plantation establishment; this is especially true where fertile pastures with high soil carbon levels and a high proportion of labile soil carbon are replaced by forest. As the plantation grows, soil carbon is replenished from litter fall and root turnover, and the soil carbon pool will approach a new equilibrium, that may be higher or lower than under pasture.

The pattern of soil carbon dynamics, both the short term temporal changes and long term equilibrium, will depend on:

- climate - which influences plant growth and turnover rate of organic matter;
- soil type - which affects plant growth and protection of organic matter;
- plant species - litter turnover is affected by the carbon:nitrogen ratio and other determinants of litter quality; and
- rainfall - loss is less likely in low rainfall environments (Guo and Gifford 2002).

Research indicates that, in general, soil carbon does not change, or increase, when broadleaf tree species are planted but that SOC is generally restored to the original stock after 30 years (Paul *et al*. 2002). In contrast, evidence suggests that reforestation with pine species generally leads to around a 15% decline in soil carbon stock (Guo and Gifford 2002; Paul *et al.* 2002). However, this conclusion is based on limited data, and so needs to be verified.

Possible explanations for lower SOC under plantations (particularly pines) compared with pastures, reviewed by Cowie *et al.* (2006) include:

(i) lower input of carbon to the soil due to reduced allocation of fixed carbon to the roots, slower turnover of roots, slower decomposition of surface litter due to lower “quality” or due to cooler and drier conditions under forest, or due to inhibition of soil fauna; and

(ii) enhanced rate of loss of soil carbon, due to reduction in physical protection as aggregation is reduced, or enhanced oxidation by ectomycorrhizal fungi associated with *Pinus radiata.*

(iii) the effect may also be indirect, arising from a decline in productivity due to loss of nitrogen from the site as a result of asynchrony of

> supply and demand: nitrogen supply is greatest soon after plantation establishment as the pasture litter mineralises, when tree requirements are small and root exploration is limited, so nitrogen may be lost through leaching.

Recent unpublished data (Singh, Cowie) do not support a uniform assumption of 15% decline where pastures are converted to pine plantations: data from high rainfall pine plantations indicate that soil carbon is in fact higher than on the adjacent pasture, in contrast with some published experimental and modelling studies. Clearly further research is required to understand and predict soil carbon dynamics in reforestation for different soil types/environments.

6. Interactions of soil carbon sequestration with nitrous oxide and methane emissions.

6.1 Non-CO_2 contribution:

In Australia, nitrous oxide (N_2O) and methane (CH_4) are significant non-CO_2 greenhouse gases, contributing 4.3% and 20.2%, respectively, to Australia's total greenhouse gas emissions. In NSW, N_2O emissions contribute 3.3% and CH_4 emissions contribute 22.2% to total NSW emissions. As the global warming potential of N_2O and CH_4 is 298 and 25 times (respectively) greater than the equivalent mass of CO_2 in the atmosphere (Forster *et al*., 2007), small reductions of their emissions could potentially provide significant benefits for the environment. Agriculture and forest soils are a significant source of nitrous oxide emissions. In contrast, soils can be a significant sink for methane.

Nitrous oxide:

Nitrous oxide gas is produced in soil through nitrification and denitrification. These processes are thought to occur simultaneously in soil, with the first taking place in aerobic conditions and the latter process confined to suboxic and anoxic conditions. Many studies have proposed denitrification as the major contributor to soil N_2O emissions, especially when oxygen is limited in soil (water-filled porosity of 60-70%). However, under aerobic conditions (e.g. at water-filled porosity of 50% or less), nitrification can be a major source of soil N_2O emissions (Dalal *et al.* 2003).

Nitrogen fertilisers, biological nitrogen fixation by legume species, organic N and the excreta of grazing animals are all sources of nitrogen that can lead to N_2O emissions from soil. The factors that significantly influence agricultural and forestry emissions of N_2O are the nitrogen application rate, crop type, fertilizer type, recycled organic type, soil organic C content, soil pH and texture[2].

Methane:

Methane flux measured at the soil/atmosphere interface is the net effect of two processes i.e. methane production by methanogens and methane uptake by methanotrophs (Knowles 1993). Both methanogens and methanotrophs are ubiquitous in soils, can prevail under unfavourable conditions to their activity, and may occur in close proximity to each other (Dalal *et al.* 2007). A net negative CH_4 flux, i.e., uptake (consumption) of CH_4 by soil methanotrophs, occurs when the

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[2] See review by Dalal *et a*l. 2003

magnitude of the CH_4 uptake process is larger than methane production (Chan and Parkin 2000).
Aerobic, well-drained soils are usually a sink for methane, due to the high rate of methane diffusion into such soils and its subsequent oxidation by methanotrophic microorganisms (Dalal *et al.* 2007). In contrast, methane production in soil occurs mainly under anaerobic environments. Large emissions of CH_4 are common where anaerobic conditions are favoured (e.g. wetlands, rice paddies and landfills), coupled with high temperatures and presence of soluble carbon, thereby supporting high activity of methanogenic microorganisms (Dalal *et al.* 2007). Globally, soils are a net sink for CH_4, and are estimated to have consumed 30 Mt CH_4 yr^{-1} during 2000-2004, equivalent to 5% of the annual load of CH_4 to the atmosphere (Denman *et al.* 2007).

6.2 Land use and management impacts on greenhouse gas emissions:

The capacity of soil to act as a source/sink for N_2O and CH_4 can vary with land use and management practices (Liebig *et al*., 2005; Saggar *et al.,* 2007; Schutz *et al*., 1990), and the interaction between fluxes of CH_4 and N_2O, as well as CO_2, can be complex (Tang *et al.* 2006). For example, if nitrogen-based inorganic fertilisers and/or organic amendments are applied to enhance plant growth, this may lead to more carbon sequestration in vegetation as well as in soil, but such benefits could be partially or completely offset by increased emissions of N_2O (Dalal *et al,.* 2003). It is also known that higher rates of nitrogen application may suppress oxidation of CH_4 by soil methanotrophs, especially in aerobic soils (Bodelier and Laanbroek, 2004).

Afforestation of pasture or cropping land may reduce nitrogen input and soil nitrogen mineralization, for example through the input of wider C-to-N ratio litter and due to reduced additions of nitrogen through fertilisers, nitrogen -fixing plants, and excreta of grazing animals (O'Connell *et al.* 2003). Hence, this type of land use change may potentially decrease N_2O emission and enhance CH_4 oxidation.

In general, CH_4 oxidation rates are greater in forest soils than in tilled agricultural soils (Suwanwaree and Robertson, 2005). However, disturbance during land preparation and harvesting/logging operations may result in accelerated mineralization of soil organic matter and release of inorganic nitrogen (Hütsch 1998; Pu *et al*., 2001). This may temporarily convert plantation lands into a significant source of greenhouse gases and may reduce the CH_4 sink capacity of soil, mainly due to adverse effects of high nitrogen availability and soil disturbance on methanotrophic activity (Hütsch 1998; Suwanwaree and Robertson 2005).

The complex interactions among these gases can justify our argument that it is the total greenhouse effects for certain mitigation practices that should be accounted for rather than judging sequestration potential of a practice from accounting a single greenhouse gas emission reduction.

6.3 Some estimates of non-CO_2 emission mitigation through reforestation in Australia

Collaboratively, scientists from NSW DPI, CSIRO and QDNRW have recently studied the effects of afforestation of grazed pastures on *in situ* flux of N_2O and CH_4 from soil in three major plantation ecosystems in Australia, including *Pinus radiata* (NSW), *Eucalyptus globulus* (WA), and *Corymbia citriodora* (Queensland).

The average soil N_2O and CH_4 emission rates were estimated at: (i) 516 kg CO_2e of N_2O ha^{-1} yr^{-1} and -22 kg CO_2e of CH_4 ha^{-1} yr^{-1} for a range of pasture sites, and (ii) 366 kg CO_2e of N_2O ha^{-1} yr^{-1} and -38 kg CO_2e of N_2O ha^{-1} yr^{-1} for the adjacent afforested pasture sites of different ages (unpublished data).

Considering the current 340,000 ha of the combined hardwood and softwood planted area in NSW as well the above estimates of the difference in N_2O and CH_4 gas fluxes between pasture and plantation, the current annual greenhouse mitigation can be equated to about 15.4 kt C (56.5 kt CO_2e) through reforestation. This greenhouse mitigation will be in addition to sequestration of carbon in accumulating woody biomass in plantations versus pasture.

In Australia, the total area under plantation forestry was around 1.7 million ha in 2006 (softwood 56.9% and hardwood 42.6%) (Bureau of Rural Sciences 2006). Since then, this resource base has been expanding rapidly at around 80,000 to 100,000 ha annually. Considering the current estimates at about 1.8 million ha of the combined hardwood and softwood planted area in Australia, the current annual greenhouse mitigation can be equated to about 81.7 kt C (300 kt CO_2e) through reforestation.

7. Knowledge Gaps, Barriers and Government Policy

7.1 Knowledge gaps and barriers

SOC inventory of NSW agricultural soils

There is a lack of detailed information on the SOC stock in NSW agricultural soils, particularly in the format applicable to carbon accounting as required by the Kyoto protocol, namely total organic carbon in mass C per unit area to 30 cm (in t/ha over 0-30 cm depth). Historically soil carbon for diagnostic purposes carried out by NSW Agriculture and other commercial soil testing services is tested to mostly only 10 cm depth. A number of very different methods have been used for measuring soil carbon. The bulk density of the soil which was tested for SOC was rarely measured and the location of the soil sampled was often not recorded.

SOC sequestration rates and management practices

Accurate estimates are needed for the rate of SOC sequestration as a result of changes in management practices and landuse. Such data are usually obtained from long term trials (Smith *et al.* 2007). However, there are very few long term trials in NSW in which SOC have been monitored as a function of management practices. There is an urgent need to obtain this type of data for the purpose of identifying management practices/farming systems with higher potential for SOC sequestration. The limited number of current sites is also under threat due to a lack of ongoing funds.

Soil carbon and carbon pool measurement and sampling techniques

To monitor carbon changes for the purpose of greenhouse gas emissions trading, there is a need to improve the accuracy and costs of soil carbon sampling and measurement methodology. Because of the likely high spatial variability and suitability the current methodology for detecting year-to-year SOC changes is not certain. While the method for measuring total organic carbon is well established, accurate, simple and commonly available methodology for the measurement of carbon fractions (C pools) is still to be developed. Research is currently in progress to develop lower cost analytical methods for determining soil carbon fractions using mid infrared reflectance (MIR). Analysis of soil carbon fractions is also needed for soil carbon modelling.

Development and calibration of soil carbon models

Soil carbon models are useful for extrapolating field results from long terms trials into the future as well as to other locations with different climate and soil types. There are a number of soil carbon models available but their usefulness needs to be proven, and they must be calibrated for local conditions. The Rothhamsted soil carbon model (RothC) is currently used by the Commonwealth Department of Climate Change for Australia's greenhouse gas inventory, and is likely to be the preferred model for national emissions trading. Recent evaluation of the RothC model using long term trial results from Wagga Wagga showed that the stubble retention factor needs to be accurately set to adequately model SOC sequestration. Default parameters tend to over-estimate SOC sequestration in stubble retention systems but are satisfactory for stubble burnt systems (Liu *et al*. unpublished data)

Net GHG balance and benefits – interaction with other GHGs

Very often one management practice that alters the SOC sequestration rate can also affect other GHG emissions. For example it is now known that no-tillage can affect N_2O emissions as well as soil carbon levels. Therefore the impact of management practices on all GHG needs to be assessed so the net GHG balance can be assessed.

There are few Australian studies that have measured the extent of N_2O emissions from planted or native forests, in comparison with pastoral and cropping systems. Estimates of N_2O emissions are highly variable and accurate data on N_2O emissions from soil are required to devise appropriate mitigation and adaptation policies. Similarly, there are few studies in NSW and across Australia that have measured rates of methane exchange from forest soils, or after afforestation of agricultural lands (Simpson 2005) particularly given that afforestation of ex-pasture lands is occurring at a significant rate in Australia (Dalal *et al*. 2003).

Land use change and associated silvicultural practices (eg nitrogen fertilisation, tree planting and harvesting operations, burning of slash, tree species), and other factors such as time since conversion to plantation and seasonality, can significantly alter rates of soil organic matter mineralisation, nitrification, and CO_2, N_2O and CH_4 fluxes from soil (Dalal *et al.* 2003; Tang *et al.* 2006). Thus it is important to quantify the total greenhouse effects of the silvicultural practices involved and to also further our understanding of important controlling factors affecting greenhouse gas emissions through carefully designed laboratory and field-based experiments.

Currently, there are a few measured and modelled estimates of the extent of N_2O emissions and CH_4 uptake in different cropping systems in NSW. In addition to measuring soil carbon sequestration of beneficial cropping sequences and associated management practices, there is a need for research to evaluate the overall greenhouse benefits of such practices, that is, including impacts on nitrous oxide and methane fluxes. There is also a need for better understanding of drivers of greenhouse emissions in agricultural and forest ecosystems so that models can be parameterised for better greenhouse predictions at a larger scale.

SOC distribution – variability

SOC levels tend to vary spatially (horizontally and vertically), at micro as well as macro scales, as well as from season to season even under natural conditions. This is due to the large number of factors including climate, vegetation, topography, soil properties, and drainage. Furthermore, in order to estimate soil carbon stock per unit area, we also need to measure the bulk density of the soil - another soil property which can have high degree of variability. It is against this background of high variability (noise) that we have to measure the rate of SOC sequestration due to management practice changes over time.

Given the likely SOC sequestration rates expected of many management practices (<1 t/ha/yr, Table 1), it is difficult to measure year-to-year variation in SOC stocks due to the effect of a specific management practice with certainty. This highlights the importance of long term field experiments to be able to determine rates of change in soil carbon and to test and refine soil carbon models.

Efficient sampling designs can be developed to verify soil C changes at any scale but the cost involved could be prohibitive (Fig. 2).

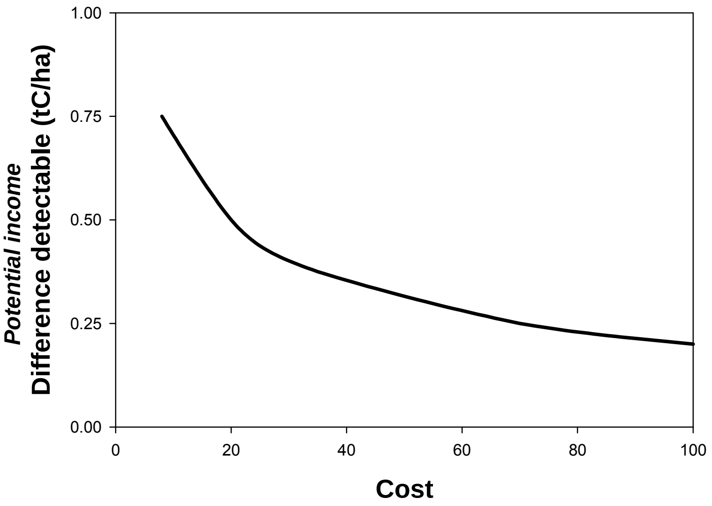

Fig. 2 Conceptual relationship between precision and cost in SOC measurement

Development of low cost and accurate technology alternatives for SOC measurement may help to bring down the cost of verification. Meanwhile, as we have a good understanding of the science controlling SOC dynamics, an integrated approach of modelling and actual measurement offers the best alternative for accurate, cost-effective quantification and decision support capabilities.

7.2 Government policy

It is becoming clear that despite of the considerable biological SOC sequestration potential in agriculture, little of this can be realised without other incentives for landowners. One of the reasons is that SOC sequestration requires costs which are, in many cases unlikely to be borne by farmers. Smith *et al.* (2008) shows (Fig. 3) that even at a carbon price of US$100 t CO_2-e, only 72% of the total global agricultural potential (including soil carbon increase as well as mitigation practices) can be realised. In addition there are also social, cultural and political constraints (Smith *et al.* 2008).

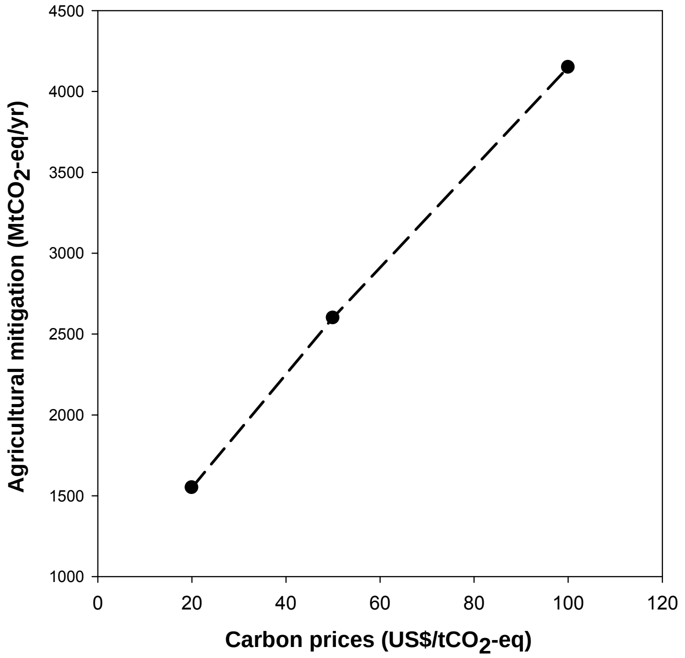

Fig. 3 Relationship between GHG mitigation potential and carbon price (constructed from data of Smith et al 2008)

8. Soil carbon in emissions trading

Soil carbon management in agricultural systems could be included in the Carbon Pollution Reduction Scheme (CPRS). Potentially it could be recognised as an eligible offset, able to generate credits, or, if/when the agriculture sector is covered, it could be used to balance emissions from other agricultural activities. It is important that soil carbon management is included in the CPRS, to provide an incentive for land managers to increase soil carbon, both for the mitigation benefits and the resulting improvements to soil health. It has been demonstrated conclusively that certain management practices can sequester soil carbon in some environments (see Section 5). Demonstration of the impacts of a range of specific management practices in different environments will allow identification of beneficial practices that should be recognised by the scheme, and therefore inform development of the scheme rules. Current research is addressing this need.

Inclusion of agricultural soil carbon management in the Australian Emissions Trading Scheme (AETS), whether as an offset or within a covered sector, will require development of cost-effective methods for estimating soil carbon change under changed land management practices. Monitoring soil carbon to document change at the project level is not feasible due to the enormous variability in carbon stocks on micro and macro scales, and the small incremental changes anticipated. Instead, estimation of soil carbon change could be undertaken by:

1. using agreed defaults for SOC stock change for specific practices, based on research studies; or
2. using process-based models of soil carbon dynamics, parameterised from experimental data; or

3. through a combination of baseline measurement to assess the vulnerability of soil carbon pools, and modelling informed by baseline measurements and understanding of the factors driving soil C dynamics.

Models that could be applied to methods 2 and 3, including RothC and Century, have been demonstrated for several Australian agricultural systems/ soil type combinations. Further testing is required to refine these models for application in emissions trading.

Several other requirements must be met to facilitate inclusion of soil carbon management in emissions trading: firstly, a practical system for assessing compliance, which could be based on evidence that practices have been implemented, rather than an audit of soil carbon stock change; and secondly, a mechanism to manage non-permanence, because soil carbon is vulnerable to future loss (this could involve a requirement to buy emissions permits if the practice is discontinued).

Current research efforts, model development and progress in devising effective emissions trading mechanisms will enable a system for emissions trading based on soil carbon management to be implemented within the AETS.

9. Conclusions

Based on limited local data and overseas experience, considerable SOC sequestration potential exists in NSW agricultural land. The highest potential exists in pasture land in the higher rainfall regions (>450 mm), both as permanent pastures or as ley pasture in the cropping zone. Considerable increases can be achieved by pasture improvement and improved management practices. Significant SOC potential also exists in the low rainfall rangelands which comprises nearly 50% of NSW. Much of the rangelands are in degraded state and considerable SOC sequestration can be achieved for a small rate of sequestration per hectare.

In addition, SOC can be sequestered by adopting new land conversion and soil amelioration options including bioenergy crops from perennial vegetation, recycling organics such as biochar, and by ameliorating sodic and acid soils. The various sink options, opportunities and existing policy drivers and the barriers are summarised in Table 4.

The promotion of conservation tillage practices (no-tillage) are important to halt further carbon emissions from cropping soils despite the limited potential of these practices to sequester carbon. Many of the management practices that are effective in increasing SOC in agricultural soils also improve productivity and profitability, conserve the resource base and protect the environment.

In order to support a role for soil organic carbon in emissions trading, there is an urgent need to resolve several key research issues:

- developing low cost methods of accounting for soil carbon;
- quantifying net carbon sequestration under different management practices for different soil types, climates and agricultural systems;

- supporting existing long term cropping rotation trial sites and the establishment of new ones where appropriate; and
- soil carbon models need to be updated to account for locally relevant agricultural management practices.

The extent of actual SOC sequestration achieved on NSW agricultural land will depend crucially on future government policies. These could be inclusion of agriculture in an emissions trading scheme, either as a covered sector, or as an offset provider. It is important to resolve outstanding research questions as a matter of urgency, to remove this barrier to inclusion of soil carbon in emissions trading.

Complementary measures, such as Research and Development to improve the role of perennial pastures in farming systems, extension to improve adoption of existing techniques or subsidies to accelerate the adoption of conservation farming equipment, should be contemplated.

Table 4. Possible C sinks, opportunities, existing drivers and barriers for SOC sequestration in NSW

Possible sinks/activities	Opportunities/existing drivers	Barriers
Cropping land	Currently C 'source' Conservation farming; Stubble initiative of EG Graham Centre	Heavy stubble handling and management, costs for adoption
Pasture Land	Improved pasture productivity; Environmental incentives - Move to increase perenniality; Relation to dryland salinity control	SOC benefits need to be quantified for various management and geographical areas
Rangelands	Large area involved; Restoration of degraded areas	Costs; research needed on SOC and management
Environmental and rehabilitation programs	Recycling of "organics" – government legislations on waste minimisation Landcare; Dryland Salinity Program Trees on Farms; Revegetation Erosion and nutrients Control – buffer strips, Agroforestry	Cost of transport, markets (acceptability by rural sector); SOC sequestration values needed to be quantified
New initiatives	Bioenergy crops	New industry/technology; research need on SOC benefit of biochar and land conversion
Soil Amelioration	Sodic soils; Acid soils – improved land value and overcoming land degradation problem	Yield increases; technology of amelioration known, low adoption, costs, soil C sequestration rate uncertain

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