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Soil Carbon Sequestration under Pasture in Southern Australia

Prepared for Dairy Australia

Project MCK13538

In conjunction with Dr Warren Mason

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1. Introduction

This review of literature about carbon sequestration was commissioned by Dairy Australia, via Dr Warren Mason, in December 2009. Details of the request are shown in Appendix 1.

The main focus of the review is on issues associated with soil carbon sequestration for climate change abatement in the dairy industry of southern Australia. The likely challenges and opportunities for dairy farmers are explored.

The following issues are discussed:

- The basic facts about soil carbon;
- Community concerns about climate change and the political response;
- Claims from some influential soil carbon enthusiasts;
- Comments from the sceptics who believe that before committing to policies with major consequences for the farming community, we must analyse, question and probe the available evidence about soil carbon and associated issues;
- The foundation provided by peer-reviewed scientific literature associated with the soil carbon debate;
- Examples of the application of reputable 'soil carbon science' to Australian farms by local soil scientists;
- Institutional arrangements to deal with soil carbon challenges.

In the concluding section, a layperson's version of the information is presented. The extent to which soil carbon sequestration options can be built into existing dairy farming systems is assessed, with an emphasis on risk management.

2. "Soil Carbon 101"

Introduction

Soil carbon sequestration is gaining global attention because of the growing need to offset the rapidly increasing atmospheric concentration of carbon dioxide (CO_2). This carbon dioxide enrichment is associated with an increase in global warming potential and changes in the amount and effectiveness of precipitation[1]. The increase in atmospheric carbon dioxide concentration also is reducing pH and carbonate ion concentration in the ocean and may adversely affect key marine organisms[2].

The 36% increase in atmospheric carbon dioxide concentration – from a pre-industrial level of 280 ppm to 380 ppm in 2006 – has been caused mainly by fossil fuel combustion, land use conversion, soil cultivation and cement manufacturing[3].

Table 1 shows the size of the global carbon pool and changes due to human activities.

The development of the soil carbon deficit following land use conversion (eg. clearing of forest for crop production) is shown schematically in Figure 1. The magnitude of this deficit is also termed the "Potential soil carbon sink capacity". Prof Rattan Lal, a US-based expert in soil carbon, states that the goal of land use and soil management from now on should be to restore the 'soil organic carbon' pool.

[1] Lal, Follett (2009)
[2] Orr *et al.* (2005)
[3] Lal, Follett (2009)

Table 1. Carbon pool size and changes due to human activities (Chan 2008a).

Carbon pool size	
Vegetation	610Gt*
Atmosphere	750 Gt
Soil	1,580 Gt
Ocean	39,000 Gt
Carbon changes due to human activities	
Fossil fuel use	+ 5.5 Gt/year
Land Use	+ 1.6 Gt/year
Rate of carbon increase in the atmosphere	
	+ 3.3 Gt/year

Source: 'The carbon cycle, climate and the long-term effects of fossil fuel burning', J F Kastings, Consequences Vol 4, No 1, 1998.
*Gt = Gigatonne, which is 1000 million metric tonnes

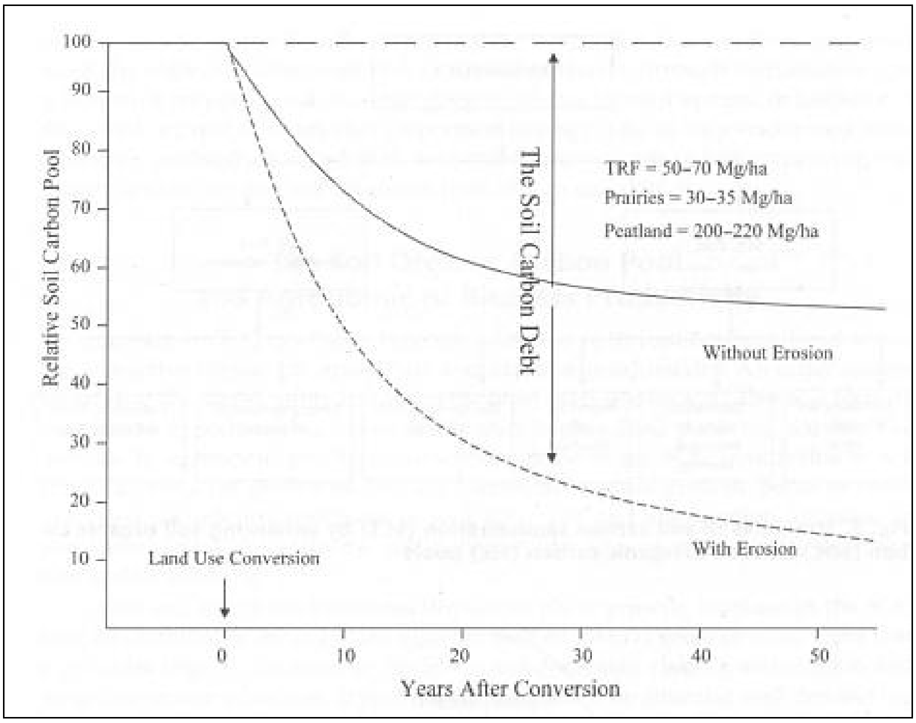

Figure 1 The soil carbon deficit, with and without erosion, following replacement of natural vegetation with farming. Typical pre-development amounts (1 metre depth) of soil carbon are listed for tropical rainforest (TRF), prairies and peatland (each is equivalent to a value of '100' on the graph) (Lal & Follett 2009).

Apart from its potential to offset anthropogenic emissions, soil carbon sequestration has numerous other benefits such as improved soil fertility for food production[4]. Specific improvements include[5]:

- Stabilisation of soil aggregates – this reduces the risk of waterlogging under moist conditions and softens the soil when dry;
- Food for beneficial organisms;
- Slow-release source of nutrients;
- Increased water holding capacity, particularly in sandy soil;
- Increase in nutrient holding capacity by improving cation exchange capacity;
- Binding of toxic cations (for example, extractable aluminium) in a form that is unavailable for plants.

The following 'facts and figures' about soil carbon are widely accepted and help all of the participants when discussing soil carbon. The main emphasis here is on the production of pasture in southern Australia.

Carbon pools and carbon cycling in pasture soil

Pasture provides a quick way to build carbon for several reasons[6]:

- Where perennial species are used, plants are growing continually rather than seasonally;
- Minimal disturbance relative to cropping;
- No erosion, if well managed.

Soil uptake of carbon dioxide involves two distinct transformations: soil organic carbon and soil inorganic carbon[7].

Soil organic carbon sequestration is through several processes:

- Photosynthesis utilises atmospheric carbon dioxide to create biomass;
- Part of the biomass is further processed into soil organic carbon contained in soil organic matter through humification and incorporation into soil aggregates.

The sequestration of soil inorganic carbon occurs through conversion of carbon dioxide in soil air into carbonic acid, and its re-precipitation as carbonates of calcium and magnesium. Leaching of bicarbonates into the deep subsoil is another mechanism for locking up atmospheric carbon dioxide. Inorganic carbon, such as calcite and dolomite, makes up about a third of total soil carbon but is relatively stable and – except when applying lime – is not strongly influenced by land management[8]. Therefore it is usually ignored when considering the effects of soil carbon on agricultural production and carbon sequestration.

It is estimated that approximately 50% of total anthropogenic emissions of CO_2-carbon are taken up by natural sinks – soil, vegetation and the ocean[9].

[4] Lal, Follett (2009)
[5] Krull *et al.* (2004)
[6] Kirkegaard *et al.* (2007)
[7] Lal, Follett (2009)
[8] Bruce *et al.* (2009)
[9] Lal, Follett (2009)

The process by which plants convert carbon dioxide into organic matter (Figure 2) is described clearly by Dr Tom Batey[10]:

> *The process of photosynthesis converts two chemicals – carbon dioxide and water – into simple carbohydrates, using sunlight as the energy source. The process takes place within the leaf and other green surfaces of plants. However, only part of the radiant energy from the sun is used in this way. At best, a plant can convert only about 6% of the total incoming solar radiation into 'stored energy'.*
>
> *Water enters the plant mainly through the roots and brings with it essential nutrients.*
>
> *Carbon dioxide enters as a gas, mainly through holes (stomata) on plant leaves. Stomata open in response to light, but close in the dark and in response to adverse conditions such as lack of water or high temperature. When a crop is growing vigorously and without constraints, a daily inflow, via the stomata, of over 150 kg/ha carbon dioxide is needed – the amount contained in the air above the crop to a height of over 20 metres. Water is lost from plants while the stomata are open – sometimes over 100 t/ha each day.*
>
> *In temperate climates, many crops increase their dry weight by about 200 kg/ha each day.*
>
> *Up to 15% of all the carbohydrate fixed by the plant leaks from roots into the soil and is utilised by soil microorganisms within the rhizosphere.*

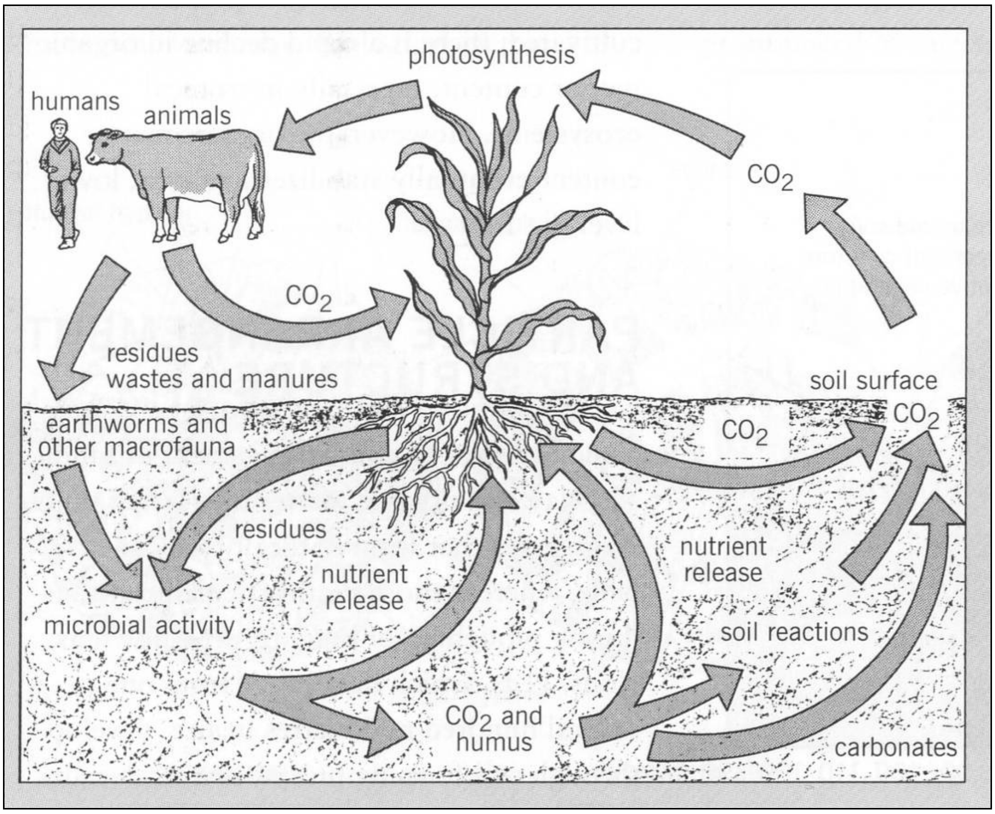

Figure 2 A simplified illustration of the carbon cycle in soil (Dubbin 2001); CO_2 = carbon dioxide gas.

[10] Batey (1988)

Plants split their energy reserves between above-ground growth and below-ground (root) growth. Root-shoot ratios of approximately 0.56 have been reported for medic pasture and grass pasture in South Australia[11]. However, subsequent grazing can have a major influence on this ratio; a prairie study in Wyoming showed that roots accounted for 85 to 91% of vegetation-component carbon[12].

Living microbes that utilise soil organic matter may comprise 1% or more of the total amount of soil organic matter present in soil[13]. The characteristics of these organisms are shown in Table 2.

Table 2. Approximate numbers and biomass of some organisms in a typical UK agricultural surface soil in a depth of 15 cm (Batey 1988).

Organism	Numbers per gram dry soil	Mass, kg/ha
Bacterias	100 million	1600
Actinomycetes	2 million	1600
Fungi, eg. mycorrhiza	0.2 million	2000
Algae	25,000	320
Protozoa	30,000	380
Nematodes	1.5	120
Earthworms	1 per kg	800

Mycorrhizal fungi can connect directly with plant roots and utilise the dissolved carbohydrates ('liquid carbon') produced via photosynthesis. They assist plants by helping to scavenge for essential nutrients such as phosphorus. Mycorrhiza produce soil glomalin, an organic compound that is important for soil aggregation and relatively resistant to decomposition (see Section 5, p. 23, for more details about glomalin).

The carbon in soil organic matter is used as food by micro-organisms. Carbon dioxide is the main product of organic decomposition in soil, but mineral nutrients also are released to make an important contribution to plant nutrition. The majority of available soil nitrogen derived from soil organic matter comes from the humus fraction[14]. Plant residues by contrast tend to immobilise organic nitrogen.

Apart from loss as carbon dioxide via microbial decomposition, soil organic carbon decline can occur through several other processes:

- Soil erosion by water and/or wind; the carbon associated with eroded soil particles may be locked up in lakebeds and seabeds, rather than being converted directly into carbon dioxide[15], but the associated nutrients become inaccessible for farming.
- Deep drainage losses of soluble organic acids.
- Photodegradation (ie. the breakdown of complex materials into simpler materials by light) is a form of oxidation that can supplement enzymatic oxidation and

[11] Crawford *et al.* (1996)
[12] Schuman *et al.* (2009)
[13] Batey (1988)
[14] www.csiro.au/resources/soil-carbon
[15] Lal (2008)

increase decomposition rates of above-ground vegetation components. As a result, organic matter decomposition in arid ecosystems is not restricted to periods of high moisture availability as is plant production[16]. Photochemical oxidation can be a risk in grazing systems unless livestock trample plant material and encourage soil contact and/or incorporation and decomposition[17].

Cultivation accelerates organic matter decomposition by exposing sites within soil aggregates that previously were protected. Dairy farmers undoubtedly are aware of the risks associated with cultivation. However, water scarcity in the Murray Darling Basin (one-third of the Australian dairy industry) means that annuals, requiring soil disturbance for establishment, are preferred to perennials. For example a study at Kyabram[18] indicated that under limited availability of irrigation water in northern Victoria, winter-growing annual pastures such as oats offer the potential to grow 70-80% of the feed grown by perennial forages (perennial ryegrass/white clover, tall fescue/white clover and lucerne) using just 40-55% of the irrigation water.

The main pools of organic carbon in soil are shown in Figure 3. A CSIRO team[19] has developed MIR spectroscopy to measure each of the soil organic matter fractions, plus inorganic carbon.

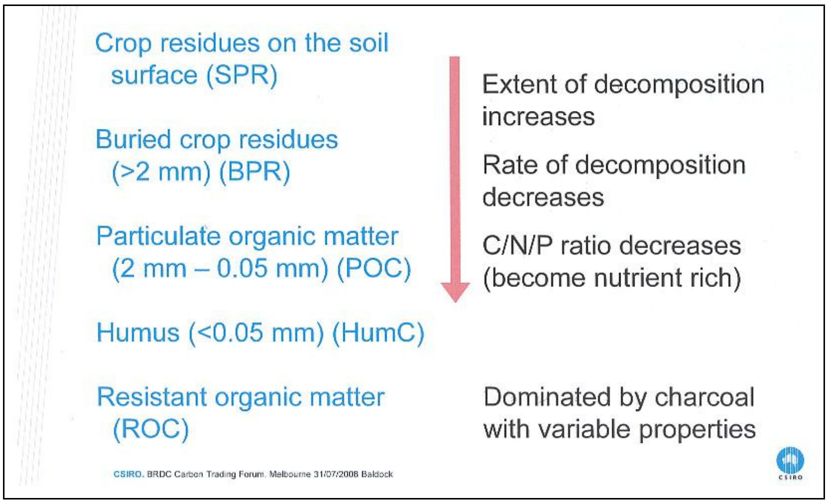

Figure 3 Composition of soil organic carbon (Baldock 2008). Resistant organic matter is also referred to as being recalcitrant; 'biochar' is included within this category. Humus is dominated by molecules stuck to soil minerals.

The ratio of C to N in soil organic matter becomes lower and much less variable as microbial decomposition progresses to create humus (Figure 4).

Examples of soil organic carbon distribution as a function of depth at selected sites across southern Australia are shown in Figure 5. Three of the four profiles had most of their organic carbon concentrated in the upper 15 cm of soil, so topsoil loss by water and/or wind erosion can drastically reduce the organic carbon reserves of poorly managed soil profiles.

16 Gallo *et al.* (2009)
17 Schuman *et al.* (2009)
18 Greenwood *et al.* (2008)
19 Janik *et al.* (2007)

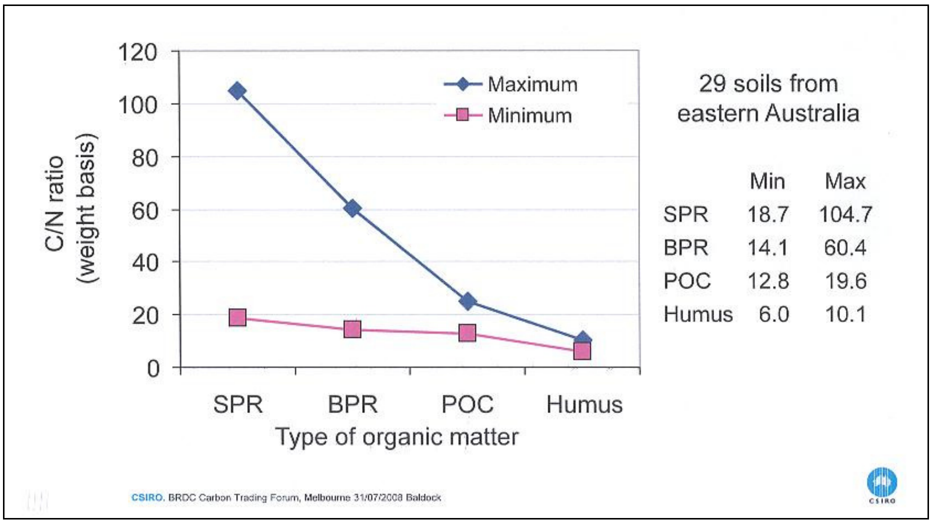

Figure 4 Carbon to Nitrogen (C:N) ratios for the carbon fractions shown in Figure 3 (Baldock 2008).

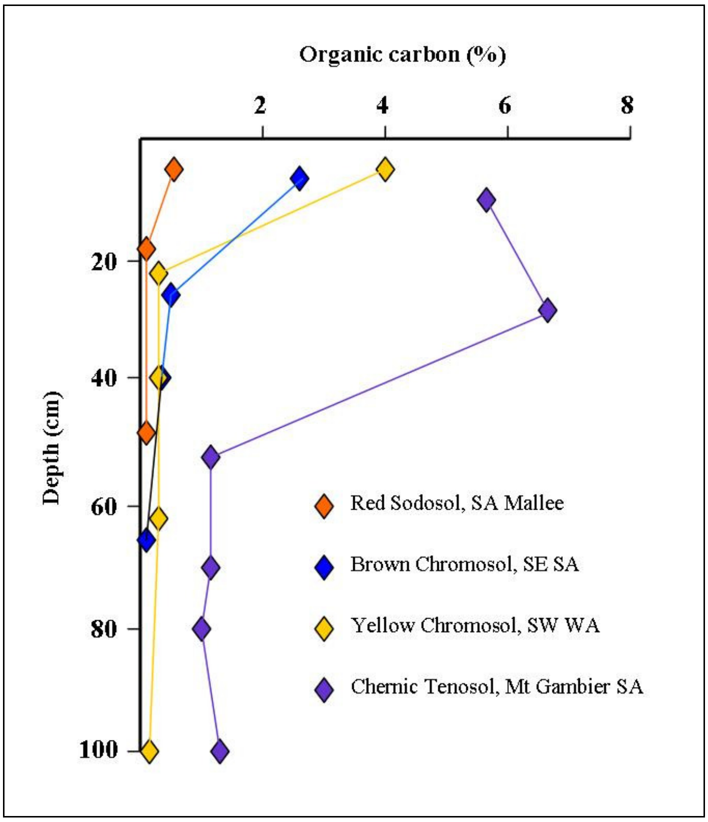

Figure 5 Examples of soil organic carbon content as a function of depth for four profiles in McKenzie *et al.* (2004)[20] that are recorded as being in areas with pasture production. The points on the graph indicate mid-points of soil horizons. The Chernic Tenosol is derived from young volcanic ash and has no problems with subsoil constraints such as sodicity and pH imbalance.

The variability of organic soil carbon across fields can be substantial and can show different patterns at different depths in the profile[21].

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[20] See pages 178, 186, 330 and 346 of McKenzie *et al.* (2004)

[21] Bruce *et al*. (2009)

Soil factors that encourage soil carbon sequestration under pasture

The magnitude and rate of soil organic carbon decomposition and sequestration depends on a range of soil and environmental factors.

To boost organic carbon concentrations in soil, two main options are available, ie. reduce decomposition and/or improve the rate of addition of organic materials. The following soil factors sometimes can be manipulated through farm management to achieve these goals.

Slow the rate of decomposition

- Clay soil tends to protect organic matter more effectively from decomposition than sandy soil. On most farms, however, increasing clay content through techniques such as clay spreading is prohibitively expensive.
- Deep soil profiles with fertile subsoil allow deep root penetration into subsoil that is much cooler (less likely to promote decomposition) than the topsoil in summer. The presence of restrictive layers such as unweathered bedrock and/or hostile subsoil conditions (eg. salinity, severe acidity) often prevents deep root penetration. Subsoil modification can overcome these constraints, but the cost often is very high.
- Anaerobic (swampy) soil has lower rates of organic matter decomposition than well aerated soil because of a lack of oxygen for soil organisms. However, this apparently beneficial process (peat creation) may be counteracted by the production of the potent greenhouse gases methane and nitrous oxide under the waterlogged conditions. Also, waterlogging restricts the productivity of most plants.
- Organic materials such as biochar, waxy plant materials, and composted manure have chemical structures that reduce the rate of organic carbon decomposition in soil. Their use is encouraged where financial returns are expected to exceed the costs of purchase and application.

Increase the rate of addition of organic materials

- Soil amelioration can increase pasture production by overcoming physical and chemical constraints. For example, soil with favourable structure takes in and stores irrigation water and rainfall more effectively for plant growth than compacted / dispersive soil. This extra water provides potential for additional pasture production. The intensive nature of dairy farming means that where poorly structured sodic soil does occur within the industry, it generally is economically viable to correct the problems with well-targeted applications of ameliorants such as gypsum. Correction of soil acidity with lime addition is another form of soil amelioration that boosts pasture productivity and provides extra organic matter for the soil.
- Essential elements (eg. N, P, S, K, Ca) that are required for soil organic carbon and/or soil inorganic carbon transformations may have to be applied to optimise productivity.
- Livestock management interacts strongly with soil management. For example, the reduction of pasture consumption by livestock allows litter to build up. This in turn is decomposed to create extra organic carbon in the soil.

Closely interacting with soil properties are climate factors, particularly temperature and rainfall;

- Soil organic carbon sequestration rate is higher in soils of cool and humid climates, relative to those of warm and arid climates – the rate of decomposition of organic matter by soil organisms under moist conditions tends to increase as soil temperature becomes greater. The optimum for decomposition in temperate climates is 25-30°C; little decomposition takes place below 10°C[22].
- The rate of formation of secondary carbonates is higher in soils of arid and semi-arid climates than those of subhumid and humid climates – soil in hot dry climates tends to have minimal deep drainage, which can lead to precipitation of dissolved carbonates within the root zone. Where irrigation water is applied to a pasture paddock and negligible deep drainage occurs, the carbonate salts that it carries will precipitate in the root zone. However, this cannot be counted as sequestered atmospheric carbon because it is river water carbonate that otherwise would have flowed out to sea.
- Where soil has structural problems such as sodicity and compaction, the amount of rainfall entering a soil ('effective rainfall') may be greatly reduced unless amelioration occurs.

In Australia, net primary productivity of agro-ecosystems is controlled mainly by climate and soil nutrient availability[23]. Figure 6a shows estimates of net primary productivity in Australia with current agriculture and climate. Figure 6b shows the ratio between current net primary productivity and that predicted without agriculture (ie. no irrigation, fertiliser addition or off-takes). While agriculture has increased productivity in many areas (in some cases almost doubled), the combination of removal of vegetation and land cultivation has generally depleted biomass and soil organic matter. The latter is vulnerable to loss via erosion because it is concentrated in the surface horizon.

The following observation has been made[24]: "*It is a great irony that in Australian agriculture, where the shortage of both water and nutrients greatly restricts yield, it is the loss of both precious water and nutrient beneath crops and pastures that is the fundamental cause of problems such as salinity and acidification. We can turn what is wasted into wealth*." On the other hand, we have to be realistic about the proportion of say a 10-year period that is available for the capture of these resources so that extra biomass can be produced.

Handy carbon calculations

One tonne carbon = 3.67 t carbon dioxide (CO_2) equivalent[25]

Tonnes carbon per ha = % soil organic carbon × soil bulk density × sampling depth (cm)[26]

'% Soil organic matter' = 1.72 × '% soil organic carbon'

In terms of 'global warming potential', nitrous oxide (N_2O) is equivalent to 310 units of CO_2 and methane (CH_4) is equal to 23 units of CO_2[27].

[22] Batey (1988)
[23] McKenzie *et al.* (2004)
[24] Williams, McKenzie (2008)
[25] Chan (2008b)
[26] Chan (2008a)

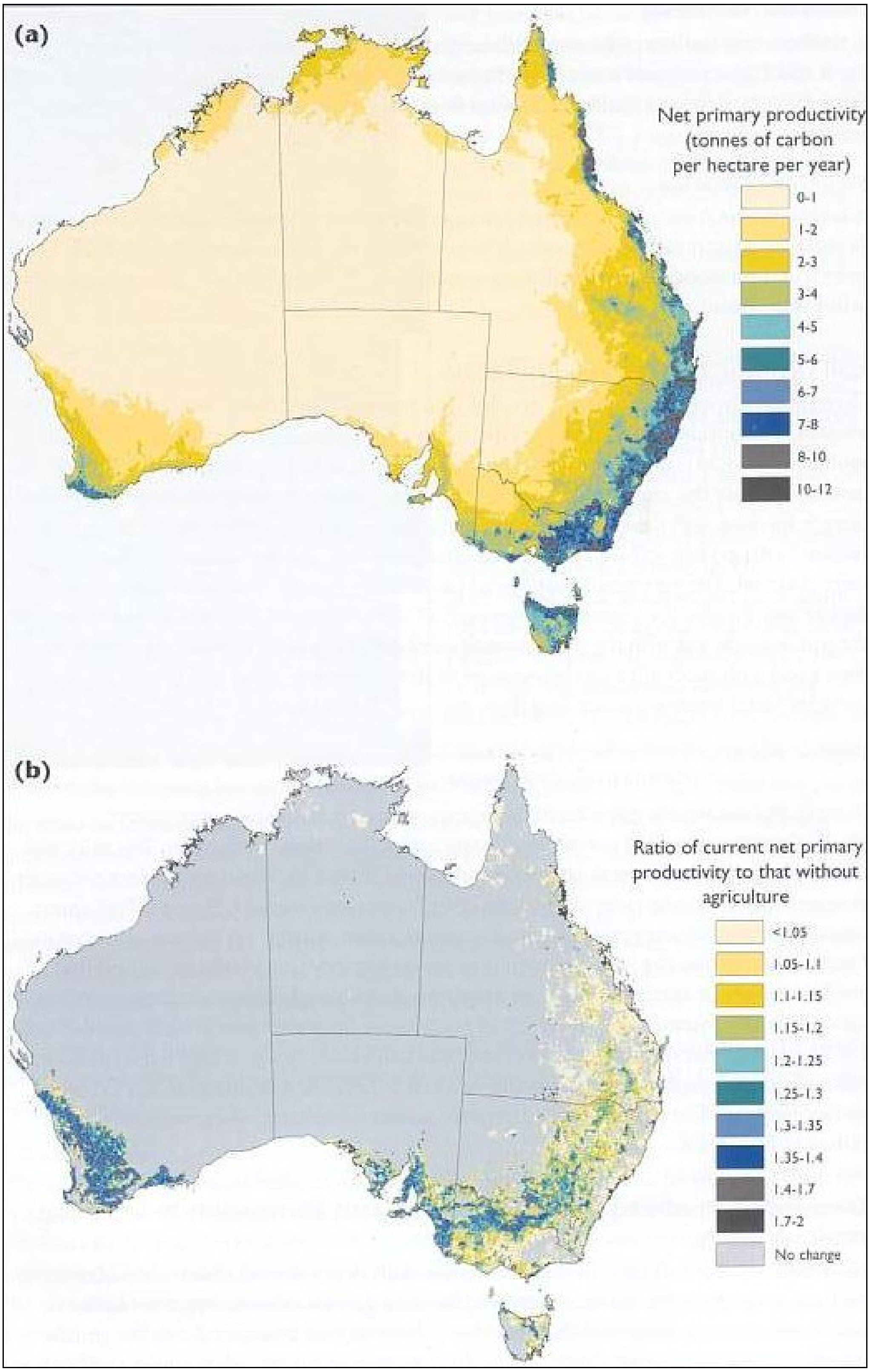

Figure 6 (a) Predicted mean annual net primary productivity of Australian ecosystems under the current climate and agricultural systems, and (b) ratio of current mean net primary productivity to that without agriculture (high-ratio areas are due to additions of fertilizers) (Raupach *et al.* 2001; cited by McKenzie *et al.* 2004).

[27] Grace (2008)

Frequently asked questions

What carbon trading price would be required to provide financial returns that match existing options for dairy pasture production?

The figures in Table 3 suggest that for carbon trading to be economically attractive for a dairy farmer, the carbon price would have to be at least $200 per tonne CO_2e. The price during January 2010 on the Chicago Climate Exchange (CCX), with no requirement for soil testing in the verification process, was just US$0.15 per tonne CO_2e. On the European Climate Exchange (ECX) the price in December 2009 was approximately 14 euros (~US18.00) per tonne CO_2e.

Table 3. Value of several options for the utilisation of one tonne of pasture

Uses for one extra tonne (dry weight) of high quality pasture	Approximate gross value of one tonne of pasture
a. Produce hay bales	$150
b. Feed to cows and convert into milk (750 litres)	$260
c. Allowed to decompose on the soil surface to produce soil carbon (traded on a one-off basis at <u>$25 per tonne</u> CO_2e)*	$21 (1 × 0.45 × 0.5 × 3.67 × 25)
d. Allowed to decompose on the soil surface to produce soil carbon (traded on a one-off basis at <u>$250 per tonne</u> CO_2e)*	$206 (1 × 0.45 × 0.5 × 3.67 × 250)

* Assuming that the one tonne pasture, when dry, contains 45% C; and ends up with 50% decomposition to create <u>0.23 tonne soil carbon</u> (a mix of particulate organic matter and humus). One tonne C = 3.67 t carbon dioxide equivalent (CO_{2e}). It is assumed here that the four options would have the same amount of root material associated with the extra tonne of pasture DM production.

It is important to note that the cost of the fertiliser used to produce the extra tonne of pasture has to be taken into account when calculating the costs and benefits of the scenarios outlined in Table 3. It is shown below in Section 6 (Kirkby) that 1 tonne C as humus requires sequestration of 83 kg N, 14 kg S and 20 kg P. Using late-2009 fertiliser prices[28], this gives a nutrient input cost of about <u>$150 per tonne of humus-C</u>. If the soil organic carbon is dominated by particulate organic matter, the ratios shown in Figure 4 suggests that a nutrient value of <u>$80 per tonne of soil carbon</u> is appropriate for the examples (options c and d) shown in Table 3. Therefore, the 4 options in Table 3 would have a <u>nutrient cost of about $20</u> associated with the one tonne of pasture that converts to 0.23 tonne soil carbon for options c and d.

In September 2008, however, the cost of nutrient inputs was about 70% higher than the late-2009 figures used in the Table 3 example. Future production limitations for fossil fuels

[28] Dairy Australia (2009): With late-2009 fertiliser prices (urea, 46% N = $500 / tonne; single superphosphate, 9% P = $320 / tonne; gypsum, 14% S = $100 / tonne), the respective N, P and S costs are $83, $50 and $14.

and phosphate rock, and a growing demand for these natural resources from countries such as China and India, suggest that higher fertiliser prices are inevitable.

In the case of options c and d, the expensive nutrients will have to be locked in the soil humus for approximately 100 years if it is to meet the carbon trading requirements of the Kyoto protocol. The temptation to use these nutrients through mineralisation of organic matter will intensify as the cost of nutrient replacement for pasture production becomes greater in the future.

These calculations cast doubt on the assertion by Christine Jones[29] that '*The (Australian Soil Carbon Accreditation) Scheme stands to become so lucrative that actual farming could become a secondary income for some producers.*'

How many tonnes of pasture are needed to boost soil carbon content of the topsoil from 3% to 5%?

To increase soil organic carbon from 3% to 5% in the upper 10 cm of soil, 24 t C/ha would have to be added to the soil[30]. Since plant residues contain approximately 45% C, this would equate roughly to 50 t/ha dry matter (DM). If this increase was to occur over 5 years, then an additional 10 t DM/ha above that currently being added would be required annually if no decomposition occurs. Since we know that at least 50% of the added plant residues will decompose, annual additions of approximately **20 t DM/ha** above that currently being added in an average year would be required to achieve an increase in soil organic carbon content from 3% to 5% over 5 years. Figure 7 shows that to achieve this aim from above-ground portions of pasture plants at Ellinbank– a high fertility dairy region in West Gippsland Victoria – pasture production would have to be ***tripled*** without increasing stocking rate. This appears to be an impossible challenge, particularly in drought years.

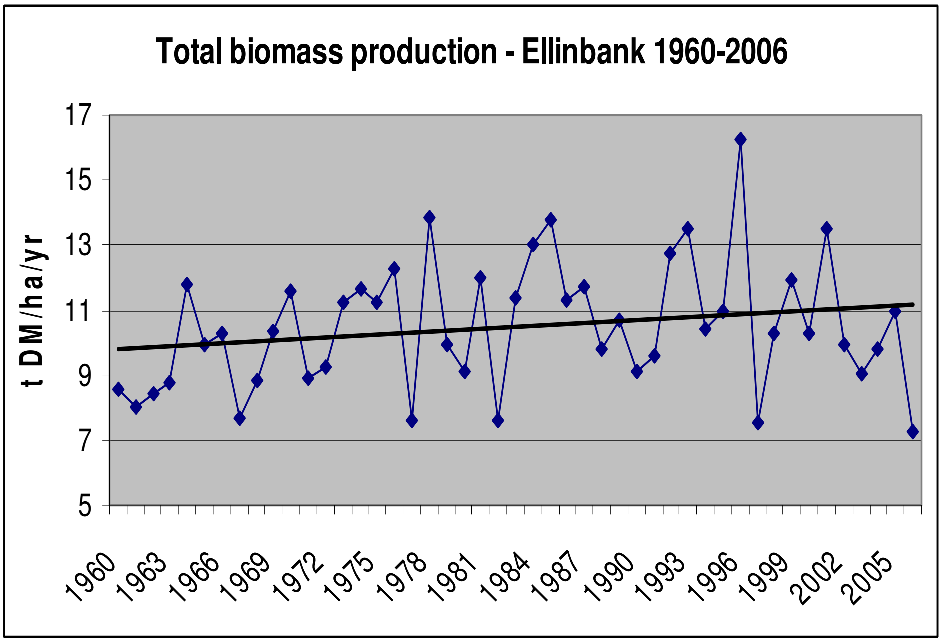

Figure 7 Total biomass production under grazed dairy pasture between 196o and 2005 at Ellinbank Vic. (Warren Mason, pers. comm.).

[29] Wallace (2007)
[30] Baldock, Broos (2008)

Can large errors occur when sampling and analysing soil for its carbon content?

Difficulties associated with soil carbon monitoring often are overlooked. The location of sampling points in a landscape must take into account spatial variability. Apart from knowing where to sample, deciding when to sample also is a challenge. Temporal variability[31] associated with cycles of drought and heavy rain needs to be taken into account when developing carbon assessment programs for entire farms and districts.

Errors in the assessment of soil carbon will affect the confidence of carbon traders and buyers.

Reasons for measurement inaccuracies (usually associated with bias rather than a lack of precision) include the following:

- Surface vegetation included with the sample, instead of being separated from the soil sample, according to Australian Greenhouse Office (AGO) protocols[32];
- Large roots (>50 mm) not separated; root material (alive or dead) <50 mm diameter roots within soil samples should be treated as part of the soil organic matter;
- Biased sampling, eg. directly beneath a grass tussock only, rather than both 'beneath tussock' and 'between tussocks';
- Failure to take into account the stone content of a soil profile;
- Mistakes in bulk density assessment, eg. accidental compression of the soil when sampling with unsuitable equipment and/or techniques, unrepresentative sampling sites;
- Calcium carbonate nodules accidentally counted as organic carbon when using the Leco method; where soil organic carbon monitoring occurs in gilgaied landscapes, the inclusion of lime nodules in soil samples can greatly boost soil carbon readings and give the false impression that the organic carbon content of a soil has suddenly improved;
- Some use the Walkley-Black analytical procedure for organic carbon analysis rather than the recommended Leco method.
- Selection of a sub-set of the results that suits the story that is being promoted;
- Failure to take into account subsoil carbon if restricting analysis to a sampling depth of just 0-30 cm;

The repercussions here are obvious. Soil sampling by operators who are not properly trained and independent can lead to spurious calculations of soil carbon tonnage in a pasture soil.

The AGO has developed a National Carbon Accounting System that includes sampling, measurement and analytical protocols for carbon estimation in soil, litter and coarse woody debris[33]. It is strongly influenced by guidelines from Intergovernmental Panel on Climate Change (IPCC), which confine soil carbon measurements to the upper 30 cm of soil. Most of the sources of error listed above are dealt with by the AGO guidelines. The main deficiency with the recommendations is a lack of guidelines about how to stratify the

[31] Creighton (2009)
[32] McKenzie *et al.* (2000)
[33] McKenzie *et al.* (2000)

sampling across different types of farms – a dairy farm obviously will require a different approach to sampling stratification than a vineyard, but no specific directions are provided. On the other hand, each rural property in Australia has its own unique features – a well-trained and experienced soil scientist would be able to provide a locally adapted stratified sampling scheme[34] that would take into account the AGO minimum standards, in addition to farmer observations and requirements on a farm-by-farm basis. Modelling can help to fill the gaps.

Once a site has been stratified, the minimum requirements for tracking soil organic carbon for accounting purposes are as follows[35];

- Collection of a representative soil sample to a minimum depth of 30 cm;
- An accurate estimate of the bulk density of the sample;
- An accurate measure of the organic carbon content of a soil sample.

A problem with the stratification step is that different operators may have different ideas about how to do it – possible inputs for the decision making process include yield maps, paddock boundaries, geology/radiometric maps and EM maps.

3. Why is there so much community interest in soil carbon?

It is widely recognised that there is a problem with too much carbon dioxide in the atmosphere and that the situation is getting worse.

Governments realise that they need to do something to address this problem on behalf of their concerned constituents.

Figure 1 indicates the rapid decline in soil organic carbon that occurs when land under native vegetation is cleared and converted to agriculture. Restoration of soil organic carbon levels (eg. through conversion of degraded farm land to forestry plantations) occurs at a much slower rate. Nevertheless, there is a theoretical potential – referred to as 'Soil carbon sequestration potential'[36] (see Figure 8) – whereby land management perhaps can lead to a return to the original pre-development soil carbon status.

The huge potential of soil carbon sequestration has generated major political interest in Australia, where voters are keen to see action by governments to minimise climate change induced by greenhouse gas emissions. Federal government leaders and their opposition counterparts have been provided with very optimistic advice about soil carbon (see next section).

The federal government, via the Minister for Agriculture, Fisheries and Forestry Mr Tony Burke, responded by allocating approximately $20 million for the 'Soil Carbon Research Program' (SCaRP) in early 2009. It is under the direction of Dr Jeff Baldock, CSIRO Land & Water. Details are shown in Section 6 (Baldock).

[34] McKenzie *et al.* (2008)
[35] Baldock (2008)
[36] Chan (2008a)

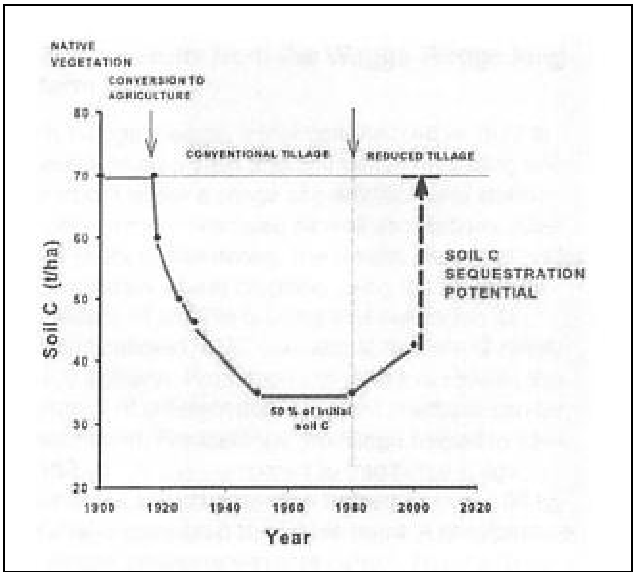

Figure 8 Historical change in soil organic carbon as a result of agricultural development, and the theoretical potential for soil carbon sequestration (Chan 2008a)

4. What are the claims of the soil carbon proponents?

Dr Christine Jones, Mr Tim Wiley

Examples of the claims from Christine Jones (a businesswoman with training in pasture agronomy) and Tim Wiley (Development Officer, WA Department of Agriculture and Food) are as follows:

1. Sydney Morning Herald, December 2009[37].

> *"Last year, in his official climate report to the Government, the economist Ross Garnaut estimated that increasing soil carbon in grazing areas and croplands could store 354 million tonnes of CO_2 a year for 20 to 50 years (equivalent to more than half of Australia's present annual emissions).*
>
> *Christine Jones is a renowned soil scientist who argues that holistic management of agricultural land can make Australia carbon neutral for decades.*
>
> *If accurate, that's enough to soak up Australia's entire post-industrial contribution to climate change - with simple landcare practices.*
>
> *Many farmers already see it as a big win and at seminars across the country are signing up to sell their soil-carbon credits. Farmers agreeing to reduced tillage, bio-fertiliser use and other soil conditioning are told to expect a 1 per cent increase in soil carbon in the top 150 millimetres of their soils - up to 55 tonnes of carbon dioxide credit per hectare."*

2. National Business Leaders Forum on Sustainable Development 28- 29 May 2009 Parliament House, Canberra, ACT; 'Pre-Forum Briefing Paper: Issues and Opportunities[38].

> *"Dr Christine Jones has stated 'Soil represents the largest carbon sink over which we have control. Improvements in soil carbon levels could be made in all rural areas, whereas the regions suited to carbon sequestration in plantation timber are limited.' She has been on a ten year*

[37] Borschmann, Pearse (2009)
[38] http://www.nblf.com.au/useruploads/files/2009%20NBLFSD%20-%20Pre%20Forum%20Briefing%20Paper.pdf

mission to raise awareness of soil carbon processes and has founded the organization Amazing Carbon and the Australian Soil Carbon Accreditation Scheme (ASCAS).

"Tim Wiley, Development Officer with Western Australia's Department of Agriculture and Food, has been undertaking work in the harshest environments in WA to show that even there soil carbon can be increased significantly. Wiley has been supporting the ASCAS trials in WA. He states that 'The trend is clear – perennial pastures sequester 5 to 10 tonnes of CO_2 per hectare annually...If all WA's agricultural soils were sequestering carbon, we would soak up WA's current emissions. This would have the potential to significantly decrease Australia's net emissions and meet our Kyoto obligations.'

This provides a sense of the potential of soil carbon. The IPCC estimates that improved productivity and conservation tillage can allow increases in soil carbon at an initial rate of around 0.3 tonnes of Carbon/ha/yr. The potential of carbon sequestration, on a global scale, is about 0.6-billion tonnes to 1-billion tonnes per year."

Christine Jones (Australian Soil Carbon Accreditation Scheme; ASCAS) advocates increasing soil organic carbon by building up humus (humified carbon) with the aid of mycorrhizal fungi, planting perennial grasses and adopting a no-till pasture-cropping farming method. The following statement was made in a submission to the Senate inquiry into climate change and the Australian agricultural sector (Dec. 2008 report): *"a change from annual to perennially based agriculture can double soil carbon levels in the topsoil within three to five years, particularly when the starting point is below two percent. Soil carbon increases of 0.5-1% could therefore be achieved relatively easily with simple changes to land management across the agricultural zones of eastern, southern and western Australia."* [39]

Jones claims that CSIRO scientists (eg. Kirkby, Baldock) are using an incorrect model of how carbon gets into the soil, the Roth C model, which ignores the contribution of liquid carbon from the cytoplasm of mycorrhizal fungi, and so provides a negative view of soil organic carbon building.

Overseas experience

Overview of 115 grassland studies in 17 countries

A review[40] of 115 studies – in 17 countries, mainly non-tropical – associated with improved grassland management practices and conversion into grassland gave the following conclusions:

- Soil carbon content increased with improved management in 74% of the studies;
- Improvements were noted for all of the types of improvement under consideration, ie. fertilisation, improved grazing management, conversion from cultivation, sowing of legumes and grasses, earthworm introduction and irrigation.
- Carbon sequestration rates tended to be greatest in the top 10 cm of soil.

Portugal

The following information, from an article entitled '*Portugal gives green light to pasture carbon farming as a recognised offset*'[41], is relevant to managers of degraded land in Australia where pasture production may be able to provide carbon credits for landholders.

[39] Cartledge (2009)
[40] Conant *et al.* (2001)

The Portugese government is paying an estimated 400 farmers for improving grassland in an area of up to 42,000 hectares with the aim of sequestering 0.91 million tonnes of carbon dioxide equivalents from 2010 to 2012. To achieve this, the farmers will use a technique known as 'sown biodiverse permanent pastures rich in legumes' (SBPPRL). Degraded soils are targeted. The system involves no-till seeding of rainfed pastures with a biodiverse mix of grasses and legumes that contains up to 20 different species and cultivars, followed by '*careful management with sustainable stocking rates*'. Trials of SBPPRL across 84 properties showed that SOM increased on average by 0.2% a year, which corresponded to 5 t/ha/year CO_{2e}.

Sheep apparently are the main grazing animals within the SBPPRL system. They return a large proportion of the material they harvest in the form of manure. This is a contrast to dairy systems where large amounts of carbon and nutrients leave grazing paddocks in the form of milk.

To reflect the limited permanence of this soil sequestration beyond the contract period, payments are about 2/3 of the price of CO_{2e} on the European Union Emissions Trading Scheme.

The developer of the SBPPRL system, Professor Domingos, notes that the system is particularly suited to soil as with low soil organic matter, and it follows that farmers who have already increased soil organic matter to saturation levels would be ineligible for the carbon payments.

Comments from the critics

1. Southern Australia is becoming warmer[42]. A rise in soil temperature increases the rate at which existing organic matter decomposes in the soil. A study in UK – reported in the journal Nature – has shown that most British soil experienced a decline is topsoil organic carbon content over the period 1978-2003, apparently because of warming[43]. The greatest losses occurred in soil with the highest initial organic matter contents. Over a similar time-span, soils on the flat and rolling pasture sites in New Zealand also have lost significant amounts of carbon to a depth of one metre[44]. In other words, it is becoming increasingly difficult to sequester organic carbon in pasture soil because of climate change.
2. There is uncertainty at the moment about the quality of Christine Jones' field measurements, data processing and interpretation of experimental results relating to soil carbon – issues upon which her advice to government is based. Jones apparently has not written any peer reviewed publications in soil science journals[45]. She is not an expert in soil science; her PhD was in pasture agronomy. Publication of claims in a peer-reviewed journal is a cornerstone of scientific credibility. Despite these reservations about Dr Jones, her views may prove to be valid under some circumstances.

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[41] Watson (2010)
[42] http://www.bom.gov.au/announcements/media_releases/climate/change/20100105.shtml
[43] Bellamy *et al.* (2005)
[44] Schipper *et al.* (2007)
[45] http://www.amazingcarbon.com/PDF/JONES-shortCV.pdf

3. Jeff Baldock thinks the level of sequestration reported by Wiley does not add up[46]. He says an increase of 7 tonnes of CO_2 equivalents sequestered per hectare per year would require a massive increase in plant growth, measured as the amount of dried plant material. "For [Wiley's] carbon numbers to be correct he would have to be producing about 8 tonnes of extra dried Rhodes grass compared to the annual pasture," he says. "I'm not going to say it's impossible but it's a big ask."
4. Even if an increase of 55 t CO_2 equiv. per hectare noted by Jones is achievable, the value ($8.25 per ha; based on a January 2010 CCX price of $0.15 per t CO_2 equiv.) is unspectacular from a farmer's point of view. The cost of the nutrients tied up in the soil organic matter (N, P, K, S) is likely to be greater than this potential financial return from carbon trading[47]. There is a lack of information about the degree of permanence of the sequestered soil carbon.
5. Technical challenges associated with sequestration of 55 t CO_2 equiv. per hectare in the Australian dairy industry are explored on page 13 of this report.
6. Fiona Robertson, in an assessment of the potential for soil carbon sequestration in the Victorian cropping industries[48], reached the following conclusion: *'With current management practices, there is little potential for soil sequestration in the Victorian cropping industry that could be used in C accounting and trading. Inclusion of pasture phases in crop rotations is the only reliable way to sequester C in soils under cropping, and it would take 10-25 years for the sequestered C (8-11 t C/ha) to become measurable'*. The study also showed that even short periods of less conservative management (eg. fallowing) could greatly diminish soil carbon stores: *'Such limitation of farm management may be overly restrictive when farmers are faced with disease and other threats to productivity, and changing market conditions'*.
7. Peter Grace has concluded that verification costs may make soil carbon sequestration non viable as a carbon trading option[49].
8. Jeff Baldock: Mycorrhiza are just one component of the millions of organisms in the soil, and soil without mycorrhizal fungi can still store carbon. However, there are circumstances where it contributes to humus formation[50].
9. Clive Kirkby: Mycorrhiza assist with P scavenging, but cannot actually create phophorus in the way that other organisms can create soil nitrogen[51].
10. The Roth C model is just one of several tools used by soil carbon scientists. It is unlikely to be used to back up important statements without local validation.

46 Salleh (2008)
47 Passioura *et al.* (2008)
48 Robertson (2008)
49 Grace (2007)
50 Cartledge (2009)
51 Cartledge (2009)

5. Details of some of the peer-reviewed science supporting our soil carbon knowledge base for pastures

Why is soil carbon being lost across entire countries such as NZ and UK?

Soil carbon losses over entire regions have been reported in UK[52] and New Zealand[53] for the approximate period 1980-2000. A similar trend is expected in Canada as conditions become warmer[54].

So far, there are no definitive answers from UK and NZ about the reasons for soil carbon losses.

However, a study in Wyoming USA[55] with similar conclusions about soil carbon loss did provide some extra detail. The data in Table 4 show that there was a loss of soil carbon from three prairie grazing treatments (exclosure, continuous light grazing and continuous heavy grazing) between 1993 and 2003. The losses were most evident after heavy grazing, where the shorter grass provided less shade and apparently led to higher soil temperatures and more rapid decomposition of soil organic carbon. The Wyoming study site experienced several years of moderate to severe drought during the period 1994 to 2003.

Table 4. Soil organic C mass under various grazing treatments (exclosure [EX], continuous light grazing [CL], continuous heavy grazing [CH]) on northern mixed-grass prairie in Wyoming (Schuman *et al.* 2009).

Soil depth	1993			2003			Change from 1993 to 2003		
	EX	CL	CH	EX	CL	CH	EX	CL	CH
cm	Mg C ha⁻¹						%		
0–15	28.2b†	35.1a	35.9a	27.3a	32.0a	26.0a	–3	–9	–28‡
0–30	47.9b	58.0a	58.3a	47.3b	54.2a	42.5b	–1	–7	–27‡
0–60	88.2b	91.9ab	101.4a	80.5b	92.5a	70.5b	–9	+1	–30‡

† Different lower case letters indicate significant differences between grazing treatments (within a year and soil depth), $p \leq 0.10$.

‡ Significant difference in C mass between years, $p \leq 0.10$.

Australian studies across the main agricultural regions are required to see if these trends are occurring locally under pasture.

Dynamics of the different carbon pools under pasture

Improvement of soil organic carbon through pasture introduction is mainly via particulate organic carbon (POC) (Figure 8)[56]. POC is broken down relatively quickly, but more slowly than crop residues. It is important for soil structure, energy for biological processes and

52 Bellamy *et al.* (2005)
53 Schipper *et al.* (2007)
54 Bhatti, Tarnocai (2009)
55 Schumann *et al.* (2009)
56 Baldock (2008)

provision of nutrients[57]. Labile (POC) carbon concentrations are maintained by constant high inputs of residues over time. Soil carbon content soon relapses after a stop or significant reduction in POC for a period of only a few years.

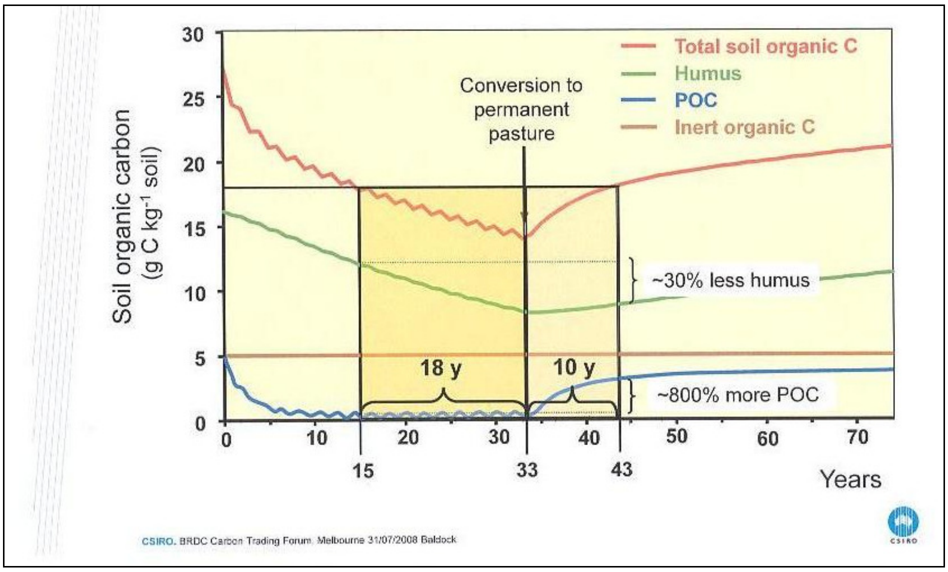

Figure 9 Changes in soil organic fractions following conversion to permanent pasture (Baldock 2008). The main point to focus on is the dominance of the particulate organic carbon (POC) increase, in relation to the much smaller humus increase, 10 years after conversion of what presumably was degraded cropping land to permanent pasture.

Figure 10 shows that the proportions of the various organic carbon fractions under pasture vary from site to site. Many Australian soils have high concentrations of charcoal from millennia of burning[58].

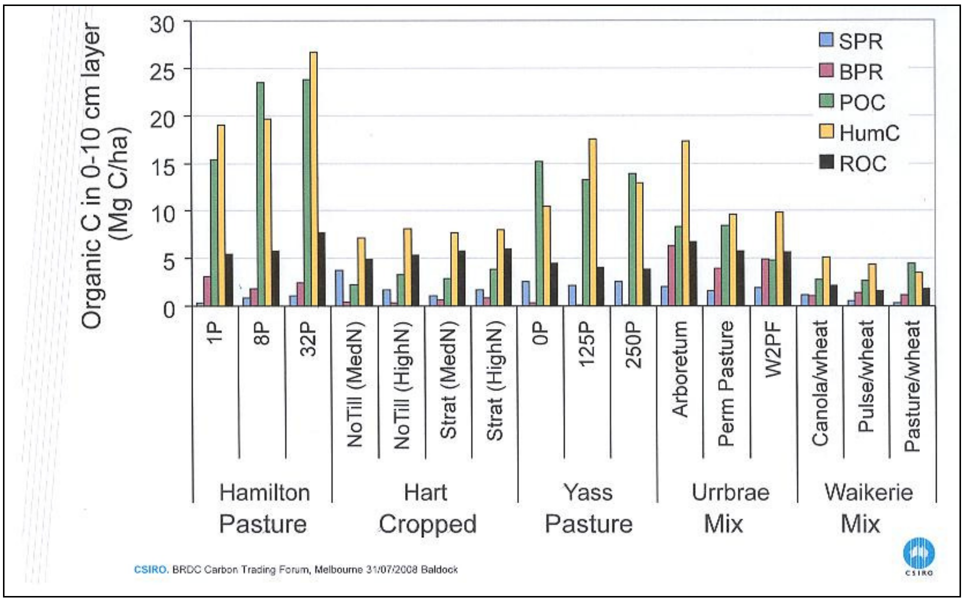

Figure 10 Variations in the amount of C associated with soil organic fractions for a range of sites in southern Australia (Baldock 2008) (*the abbreviations are explained in Figure 3*)

57 www.csiro.au/resources/soil-carbon
58 www.csiro.au/resources/soil-carbon

The organic carbon contents of soils used for dairying are typically very high, organic carbon often being in the range 3-7% in the top 10 cm[59]. This is in contrast to the majority of soils used for cropping and more extensive grazing systems.

Recalcitrant organic matter, eg. waxes including cutin and suberin, slows the rate of soil organic matter decomposition[60] and therefore makes it easier for farmers to retain carbon in their soil. If grass, legume and herb species that increase the recalcitrance of residues (particularly root material and associated biota) become available – without compromising other soil factors and nutritive value for livestock – they should be considered by dairy farmers.

A pasture site in northeastern NSW provided an opportunity to study the rate at which soil carbon is lost in relation to soil aggregation[61]. A change in vegetation cover from rainforest with a C3 photosynthetic pathway to grasses (*Paspalum dilatatum* and *Pennisetum clandestinum*) with C4 pathways (produces soil carbon with a distinctive isotopic signature) was used to follow input rates and turnover of organic matter in a krasnozem (Red Ferrosol) over an 83 year period. Turnover times for organic matter from the three sampling depths (0.0-7.5, 7.5-15.0, 60.0-80.0 cm) were calculated as 60, 75 and 276 years respectively, compared with 75, 108 and 348 years for the organic matter protected within microaggregates from the same horizons. In other words, the deeper the soil organic carbon is sequestered in soil, the longer the residence time. This was most evident where soil microaggregation is strongly developed. Disruption of these microaggregates through excessive tillage allows soil carbon previously protected from microbial action to decompose rapidly.

Modelling suggests that the increase in atmospheric CO_2 eventually will boost plant growth (in the absence of major water and nutrient deficiencies) and lead to increased soil organic matter, particularly in clay-rich soil[62].

Degree of permanence of organic carbon– implications for carbon trading

Farmers need to be aware that the increased carbon levels have to be maintained for long periods of time (70-100 years in most cases) to have any financial benefit in carbon accounting systems developed under the Kyoto Protocol[63].

Unfortunately, none of the carbon pools – with the possible exceptions of charcoal and biochar – are truly permanent when considered over a period of say 100 years on a broad range of soil types under a variety of climatic conditions in Australia.

However, greenhouse gas accounting for soil carbon in agriculture under the Kyoto Protocol is based on the rate of change in carbon stock, so if conventional practice causes a decline and the new practice reduces the rate of loss, credit can be earned[64]. This is a real reduction in emissions that could be counted under an emissions trading scheme.

[59] Dougherty W (2007)
[60] Krull *et al.* (2003)
[61] Skjemstad *et al.* (1990)
[62] Krull *et al.* (2003)
[63] Grace (2008)
[64] Chan *et al.* (2008)

The Marrakesh Accords are the set of rules governing greenhouse-gas accounting under Kyoto. The general principle is that credit should be given only for changes in the rate of carbon removed from (or not added to) the atmosphere, over and above business as usual[65].

Biochar

Biochar (a form of charcoal converted from organic material) and farmyard manure (which contains a high proportion of slowly decomposing lignin) are imported products that may boost organic soil carbon locally, but not necessarily improve total carbon sequestration because the organic soil carbon has been relocated from one area to another[66].

The pyrolysis process itself is carbon negative. However, because energy has to be expended (and paid for by the biochar recipient!) to transport organic material to a pyrolysis plant, and then to take biochar to the paddock requiring extra carbon input, full life-cycle analyses are needed to determine if there really is an overall net increase in carbon sequestration, plus profits for the landholder.

Nevertheless, biochar is creating great interest because of its ability to sequester carbon in a form that is very resistant to decomposition.

Further details are presented in Section 6 (Krull).

Glomalin from mycorrhizal fungi

Arbuscular mycorrhizal fungi (AMF) produce glomalin (a glycoprotein) within their hyphal walls[67]. As the hyphae senesce, glomalin is deposited within the soil where it accumulates until it represents as much as 5% of soil C.

Benefits of glomalin include stabilisation of soil aggregates and provision of a slow-release source of nutrients. However, it's potential for long-term soil carbon sequestration (ie. >100 years) appears to be limited. Carbon dating of glomalin in a forest soil study indicated turnover at unspectacular time scales of several years to decades[68].

Standing stocks of AMF hyphae in soil are in the order of 0.05 to 0.90 t/ha; glomalin constitutes a modest proportion (0.4-6%) of this biomass. Glomalin concentrations are positively related to net primary productivity[69]. In Australia, phosphorus is a key driver of pasture productivity, regardless of AMF status (see P-nutrition section, page 25).

A possible problem with glomalin is that it can induce water repellence in soil and adversely affect water entry[70]. Some plants do not have associations with AMF (eg. brassicas) but still add organic matter to soil.

These facts about mycorrhizal fungi and glomalin do not match the hype outlined above by Dr Jones (see Section 4).

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65 Tullberg (2007)
66 Bruce *et al.* (2009)
67 Treseder & Turner (2007)
68 Rillig *et al.* (2001)
69 Treseder & Turner (2007)
70 Rillig (2005)

Plant stones

Phytoliths, also referred to as plant opal or plant stones, are silicified features that form as a result of biomineralisation within plants[71]. The silicification results in the occlusion of carbon and renders it highly resistant to decomposition in the soil environment. Species known to be prolific producers of phytoliths include barley, sugarcane and wheat. Measurement in north-eastern NSW showed that sugarcane is able to sequester carbon within phytoliths at a rate of 0.18 tonne C/ha/year.

The significance of this process under dairy pasture appears to be unknown. However, it has the potential to be important, given the very long term sequestration period (hundreds of years) for phytoliths. Further study is required.

The fact that soil organic matter improvement does not last for long after removal of a POC-dominated pasture phase (Figure 9) suggests that current pasture varieties in southern Australia do not contain large quantities of phytoliths.

Depth of sequestration

Where soil sampling is confined to the topsoil in comparisons between minimum tillage and deep tillage, the former treatment is shown to be the most favourable for soil carbon sequestration – this forms the basis of some carbon trading schemes. However, inclusion of subsoil data shows that in some situations, deep tillage is the best technique for improving soil carbon throughout the entire root zone[72], presumably because of the presence of compacted zones that require loosening.

An analysis of approximately 2,700 soil profiles in three global databases[73] found surface soil carbon stocks to be well correlated with climatic variables, but the deeper soil stocks were not. Carbon dating has shown that deep soil carbon is consistently older than carbon near the surface, indicating organic matter may be more stable at depth. Global soil organic carbon storage in the 0-1m, 1-2m and 2-3m depth intervals, respectively were 1502, 491 and 351 Pg C. In grasslands, the total amount of soil organic carbon in the second and third metres was 43% of that in the first metre. These substantial quantities of deep subsoil carbon should be taken into account when developing carbon sequestration strategies.

Decomposition of organic soil carbon is likely to become slower with increasing depth in the soil[74]. The subsoil is cooler in summer than the topsoil. There may also be a lack of oxygen in the subsoil. Carbon loss tends to be greatest where microbial activity is high, eg. warm, moist environments[75].

In unusually wet years, water is lost via deep drainage in most Australian farming systems. On dairy farms, it may be possible to improve the utilisation of this wasted water through the use of deep rooted perennial shrubs (eg. tagasaste on light-textured soil) to sequester organic carbon deeply, and perhaps give forage as well. However, shrubs allocate biomass to woody branches that cannot be utilized by cattle – further study is needed to assess the

[71] Parr, Sullivan (2005)
[72] Blanco-Canqui, Lal (2008)
[73] Jobbagy, Jackson (2000)
[74] Bruce *et al.* (2009)
[75] www.csiro.au/resources/soil-carbon

options for the deep placement of organic carbon via the root systems of a broad range of pasture species, in a way that does not jeopardise farm profitability.

Recycling of N from the deep subsoil to the topsoil via deep rooted perennial – may lead to higher rates of topsoil mineralisation[76].

Acceleration of humus breakdown by microbial priming

A mechanism for potential mobilisation of large amounts of carbon is the so-called 'microbial priming effect'[77]. It has been shown experimentally that the action of substrates with readily available energy (eg. glucose and cellulose) to the soil stimulates the decomposition of 'old' soil carbon. A change in agricultural practice that increases the distribution of fresh carbon along the soil profile could stimulate the loss of ancient buried carbon[78].

Dairy cow urine can decrease soil organic matter[79]. It contains easily degradable carbon, which may lead to acceleration of soil carbon cycling by priming.

Phosphorus nutrition

Soil carbon gains from improved pasture nutrition may be difficult to prove during the early stages of sequestration. On an experimental site near Hamilton Vic.[80], pasture production was strongly increased by phosphorus application, which allowed a three-fold increase in sheep stocking rate and a doubling of wool production. Soil carbon sequestration was not significantly affected by either P application rate or stocking rate, even after 25 years of treatment. However, increasing rates of P application produced a trend of slowly increasing carbon sequestration that would only be detectable by soil analysis if the higher application rates were continued for periods in excess of 30 years.

Earlier work on grassland plots on solonetzic soil in South Australia[81] showed that treatment with phosphorus fertilisers and grazing with sheep resulted in large increases in the organic matter content of the surface soil (0-5 cm), but increases were small at the 15-20 cm depth interval. Similar improvements were noted on podzolic soils in the Crookwell district of NSW[82].

Dr Megan Ryan compared soil biological communities on organic and conventional dairy farms in the Goulburn Valley, northern Victoria[83]. Pasture plants (perennial ryegrass and white clover) in the biodynamic soil had a slower growth rate and a higher level of colonisation by VAM fungi due to lower initial soil P and N concentrations, ie. the fungi were unable to compensate for no inorganic P addition. There was no indication that the biodynamic and conventional soils had developed substantially different processes to enhance plant nutrient uptake or that the indigenous VAM fungi differed in their tolerance to applications of soluble nutrients.

76 Angus *et al.* (2006)
77 Heimann, Reichstein (2008)
78 Fontaine et al. (2007)
79 Lambie *et al.* (2008)
80 Graham *et al.* (undated)
81 Russell (1960)
82 Williams, Donald (1956)
83 Ryan, Ash (1999)

The importance of P in Australian grazing systems is reinforced in Section 6 (Chan).

Greenhouse gas emissions after liming and the interaction with nitrate leaching

Lamb growth rates on pure subterranean clover pastures in southern Australia are 20-30% greater than on a conventional perennial ryegrass-subterranean clover mixture[84]. However, the benefits of higher legume content come with a greater risk to the environment through nitrate leakage into groundwater, and soil acidification.

Treatment of this acidification with lime will in turn release CO_2 to the atmosphere[85].

Unexpected problems with nitrogen deficiency in high-OM soil

The Chernic Tenosol soil type shown in Figure 5 (Mount Gambier, SE SA) has unusual properties under dairy pasture[86]. Despite the high organic carbon content (humus dominated) and an apparently excellent mineralisation potential, the dairy pasture is responsive to nitrogen fertiliser. Several hypotheses are being investigated. A likely contributing factor is the exceptionally good subsoil structure that would allow rapid loss of nitrogen via leaching from the root zone.

New measurement systems for soil carbon

At the University of Sydney, measurement 'packages' are being created by Prof. Alex McBratney and his team that combine modern geostatistical techniques with new field measurement techniques – based on rapid *in situ* NIR profiling[87]. NIR-MIR scanning of soil profiles[88] allows inexpensive estimation of a broad range of soil factors, including the different soil organic and inorganic carbon fractions. Their proposed 'soil carbon and trading scheme' is shown in Figure 11.

Statistical procedures have been proposed[89] that provide consistent presentation of information about carbon concentrations and tonnages in soil profiles, and procedures for dealing with the trade-off between measurement costs and accuracy.

For example, where a farm has 4,000 +/- 800 tonnes carbon to sell, the sequesterer could be paid via an arrangement based on, say, the lower 95% confidence value, ie. 3,200 tonne carbon.

It is unclear how the degree of permanence of the sequestered carbon will be proved.

The ownership of carbon may be complicated in situations where carbon-contracted land is sold by the owner.

An alternative to on-farm measurement and monitoring of soil carbon could be to adopt a modelling approach[90]. For example, schemes could adopt standard rates of carbon dioxide abatement for the adoption of particular management activities for a length of time. Here,

84 McCaskill (2008)
85 Page *et al.* (2009)
86 Howieson (2009)
87 McBratney, Minasny (2008)
88 Janik *et al.* (2007)
89 McBratney *et al.* (2009)
90 Bruce *et al.* (2009)

the confidence of investors in the contracts is likely to be based on information about management activities rather than actual sequestration rates. However, there is a need to ensure that any scheme actually achieves the objective of sequestering carbon that truly is additional to 'business as usual' farming practice.

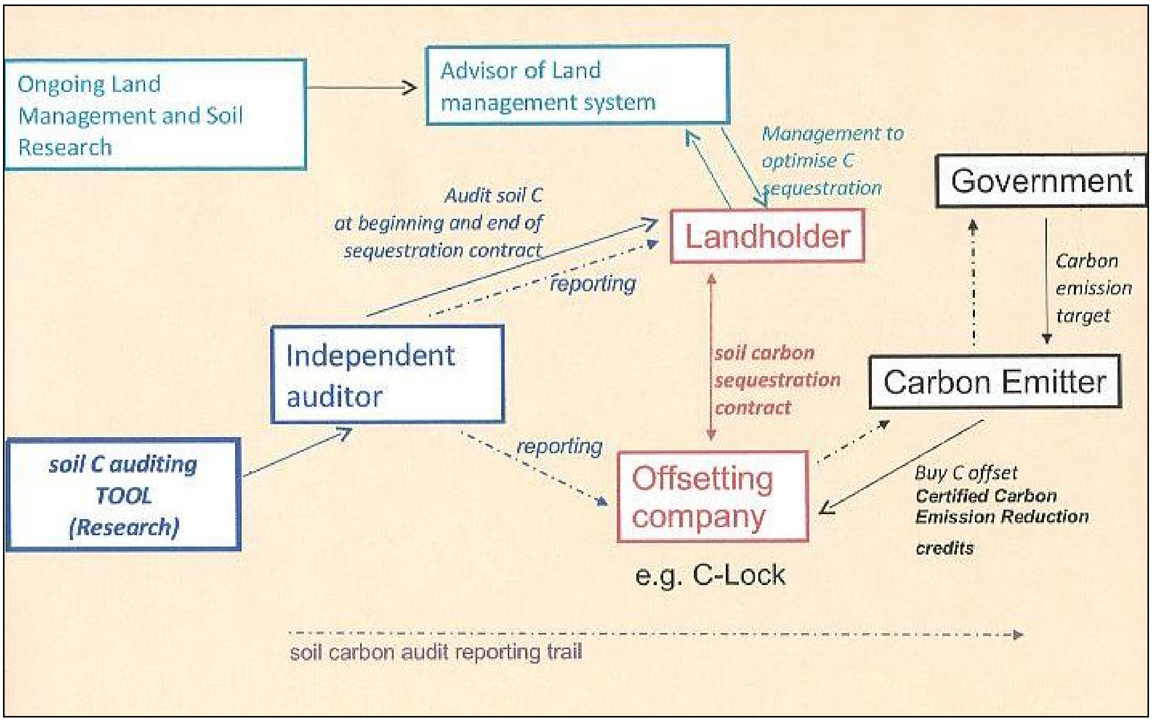

Figure 11 A soil carbon accounting and trading scheme (McBratney and Minasny 2008).

Other types of greenhouse gas emissions from pasture

Nitrous oxide

Nitrous oxide (N_2O) is a greenhouse gas 310 times more potent than carbon dioxide.

The energy required by soil microbes is usually generated by oxidation-reduction reactions, transferring electrons from the carbon atoms existing in the organic compounds to oxygen[91]. If oxygen is unavailable in the soil – ie. saturated conditions – some microbes (eg. denitrifiers) can use other oxidants as electron acceptors. After oxygen, the most readily reduced oxidant is nitrate. This denitrification process generates nitric oxide (NO), N_2O and dinitrogen (N_2). N_2O is also produced during nitrification, the microbially-mediated oxidation of ammonium to nitrate.

It has been proposed therefore that increasing C-sequestration, with an associated increase in total nitrogen, is directly linked with increasing N_2O emissions[92]. This may be true if the severity and duration of waterlogging in soil remains constant as soil organic carbon content becomes greater. It is more likely that soil structure will improve as soil organic carbon content becomes greater, thereby reducing the risk of waterlogging.

[91] Li *et al.* (2005)
[92] Li *et al.* (2005)

Topsoil and sub-surface compaction (pugging) often occurs where livestock are grazed. It has been shown, in an experiment near Orange NSW[93], that the structural quality of the topsoil under set stocked sheep grazing changed, as indicated by a decrease in total macroporosity and a smaller proportion of macropores. In contrast, stable structural conditions were maintained under rotational grazing. Arguably the 'best' soil structure for plant growth, represented by large values of total macroporosity and macropore surface area, and a large range of pore sizes, was exhibited under the pasture cages where pasture defoliation occurred in the absence of hoof pressure. It is concluded that grazing tactics are an important factor in the dynamics of soil macroporosity and the vertical continuity of macropores, as a result of the combined effects of hoof pressure and root channel development. A likely consequence of this improved soil structure is less waterlogging under moist conditions, which reduces the risk of N_2O loss via denitrification caused by anaerobic conditions.

Soil pH is a major influence on the ratio of N_2O and N_2 emissions from denitrifying soil[94]. Measurements under irrigated cotton on an alkaline clay soil near Narrabri by Dr Ian Rochester showed that only about 2 kg N/ha (~1.1% of the N applied) was lost as N_2O. Other studies reviewed by Dr Rochester showed that a greater proportion of N_2O relative to N_2 is emitted from acidic soil; approximately equivalent amounts of each gas are emitted from soil of pH 6.0. Therefore, where a pasture production system leads to acidification of a soil profile that is not corrected by lime application – eg. through excessive leaching of nitrates and/or product export from a paddock – the risk of N loss as N_2O, when denitrification occurs, is likely to become greater.

Nitrous oxide emissions from soil nitrite and nitrate resulting from residual fertiliser and legumes are rarely studied but probably exceed those from fertilisers[95].

Methane

Methane (CH_4) is a greenhouse gas 23 times more potent than carbon dioxide. It is released from soil under swampy conditions.

As the severity of waterlogging in soil becomes greater, organic matter may decompose to produce methane which is produced at a similar redox potential to hydrogen sulphide gas. This scenario appears to be very unlikely under Australian dairy pasture.

[93] Cattle, Southorn (2010)
[94] Rochester (2003)
[95] Dalal *et al.* (2003)

6. Soil scientists currently associated with the application of peer-reviewed soil carbon information to grazing and farming systems in southern Australia

This section describes the work of some of the Australian soil scientists who have helped to provide reputable information about soil carbon measurement and management in southern Australia.

They presumably are the scientists who Christine Jones has criticised via the following statement in ECOS[96]: *" ... people – including most of our top scientists – simply don't understand soil carbon sequestration or the role of the microbial bridge and have therefore overlooked it."*

Dr Yin Chan

One of the most experienced soil carbon scientists in Australia is Yin Chan, NSW Industry and Investment, Richmond. He has worked on the topic for over 25 years.

Dr Chan made the following observations about soil carbon sequestration under contrasting pasture management regimes, via paired site comparisons, on 23 farms between Gulgong NSW in the north to Albury Vic. in the south.[97]:

> *To quantify the soil carbon stocks under different pastures and a range of pasture management practices, a field survey of soil carbon stocks using a paired site approach was undertaken in the central and southern NSW as well as northeastern Victoria in 2007. Five comparisons were included namely, native vs introduced perennial; perennial vs annual; continuous vs rotational grazing; pasture cropping vs control, and improved vs unimproved pastures.*
>
> *Results indicated a wide range of soil organic carbon (SOC) stocks over 0-30 cm (22.4 to 66.3 t C/ha), with little difference when calculated based on either constant soil depth or constant soil mass. Significantly higher SOC stocks were found only as a result of pasture improvement using P application compared to unimproved pastures. In this case, rates of sequestration were estimated to range between 0.26 and 0.72 t C/ha/yr, with a mean rate of 0.41 t C/ha/yr.*

He noted the need for scientific long term trials to quantify the soil organic carbon sequestration potential of alternative pasture management practices.

In an experiment established near Wagga Wagga in 1979 and monitored for 20 years[98], Dr Chan showed that continuous wheat cropping using the traditional practice of stubble burning and cultivation, soil organic carbon was lost at the rate of nearly 400 kg/ha/year. No-tillage helped to save 169 kg C/ha/year compared to traditional tillage. Stubble retention helped to save 108 kg C/ha/year. The most carbon conserving system was wheat/subclover pasture (1:1) with the wheat under no-till and stubble retention, where soil organic carbon was increasing at a rate of 185 kg C/ha/year.

This experiment at Wagga Wagga was carried out during a period with above average rainfall and with temperatures that were cooler than experienced since 2000.

A study in 2007[99] highlighted the high soil organic carbon sequestration potential of coastal pasture soils near Taree NSW (>70 t C/ha to 20 cm depth). There was no significant

[96] Porteous, Smith (2008)
[97] Chan *et al.* (2010)
[98] Chan (2008a)
[99] Chan, McCoy (2009)

difference in soil organic carbon stock to 20 cm between paired sites of perennial pastures and native forest. More than 20 t C/ha of difference in soil organic carbon stocks were found between fertilised and unfertilised pastures as well as between 'effluent applied' and the control (Table 5).

This study on the NSW mid North Coast highlights the importance of adequate nutrition for carbon sequestration under pasture. Although further work is required to assess deep subsoil processes, it shows that impressive soil carbon concentrations are possible where reliable rainfall occurs. However, a dairy farmer who already has large amounts of soil carbon may not have much scope for further improvements.

Table 5. Soil nitrogen and organic carbon levels and properties (0-10 cm layer) and soil organic carbon stocks (0-20 cm) at two paired sites with contrasting nutrient history (Chan & McCoy 2009).

Pasture Type	Soil P, mg/kg	pH	SOC,%	Soil N,%	C/N	Carbon† stock
1st paired site						
Kikuyu (fertilised)	37	5.2	5.2	0.53	9.81	67.2
Native grass (*Bothriochloa sp*) not fertilised	9.6	4.8	2.8	0.31	9.03	44.2
2nd paired site						
Pasture irrigated with dairy effluent	220	6.3	4.5	0.18	9.18	75.5
Pasture (adjacent but not irrigated with dairy effluent)	65	6.0	2.3	0.16	10.45	54.8

† soil carbon storage (0-20 cm) in t C/ha

Dr Neil McKenzie

Neil McKenzie is Chief of CSIRO Land & Water, Canberra.

His carbon related activities include:

- Leadership of the Australian Collaborative Land Evaluation Program (ACLEP) that coordinates soil survey and monitoring activities across Australia.
- Release of the Australian Soil Resource Information System (ASRIS), an online system for soil and land resource information across Australia.
- CSIRO representative on the National Committee on Soil and Terrain and its predecessors.
- Leadership of CSIRO's involvement in the forthcoming global soil information system[100].
- Chair of the Working Group on Digital Soil Mapping for the International Union of Soil Science.

[100] http://www.globalsoilmap.net/

His views about future institutional arrangements for soil carbon assessment and management are presented below in Section 7.

Dr Jeff Baldock

Jeff Baldock works in Adelaide with CSIRO Land & Water.

He has been studying soil organic matter chemistry, dynamics and its contribution to soil productivity for more than 25 years and is the author of 70 journal articles and 10 book chapters.

Dr Baldock directs the $20-million 'Soil Carbon Research Program' (SCaRP). He outlined the SCaRP program as follows[101]:

Objectives:

- Define and use a nationally consistent methodology for quantifying soil carbon across Australia;
- Identify land management strategies with the potential to build soil carbon at regional levels;
- Quantify the inputs of carbon to soils under perennial pasture systems;
- Develop rapid and cost-effective means for quantifying soil carbon stocks (focus on MIR measurements) and measuring soil bulk density;
- Provide data for further development of NCAS (National Carbon Accounting System).

Issues associated with the perennial pasture component include:

- To increase soil carbon we need to increase the amount of carbon captured and returned to the soil.
- Under appropriate circumstances the introduction of perennials can:
  – Extend the growing season,
  – increase the proportion of the year over which carbon can be captured,
  – Alter the allocation of captured carbon to above and below ground components.
- The perennial pasture component of SCaRP will:
  – Use ^{14}C labelling to quantify the allocation of carbon to above and below ground components for kikuyu and panic/Rhodes pasture,
  – Assess the amount of soil carbon under kikuyu. Temperate plants (C3) capture carbon during photosynthesis using a different process than tropical grasses such as kikuyu (C4). This provides a basis to differentiate carbon derived from C3 vegetation from carbon derived from C4 vegetation using novel laboratory procedures.

Mr Clive Kirkby

Clive Kirkby is scientist with CSIRO Plant Industry who is enrolled for a soil carbon PhD project at Charles Sturt University Wagga Wagga.

[101] Baldock (2009)

He acknowledges that it is possible to build up soil organic carbon. However, we need to be realistic about how much soil organic carbon can be sequestered, and whether the cost of changes to management practices can be justified in relation to returns[102]. Pastures do generally increase soil organic carbon, but it soon disappears.

Humus contains substantial amounts of N, P and S; this cost has to be taken into account[103]. It is estimated that 1 tonne C as humus requires sequestration of 83 kg N, 14 kg S and 20 kg P.

The C:N:P:S ratio in humus tends to remain constant[104]. Humus decomposes by 2% to 3% per year, so a minimum of extra 2% to 3% of N, P and S needs to be added just to maintain humus at the status quo[105].

It is often limitations of the P and S that restrict C build-up in Australian soils, rather than a lack of carbon.

Dr Evelyn Krull

Evelyn Krull is with CSIRO Land & Water, Adelaide.

She has more than 10 years experience in the application of stable and radiogenic isotopes to rocks, soils and sediments to decipher organic matter processes and changes in biogeochemical cycles.

Dr Krull is currently leading two national research projects on biochar which aim to explore the effects of different biochar material on nutrient dynamics in agricultural soils as well as on the stability of different biochars, their effect on N_2O emissions and life-cycle assessment methodology.

She describes the biochar story as follows:

The heating of biomass in closed oxygen-free conditions (known as pyrolysis) [106] creates a source of energy, either in the form of synthesis gas or liquid fuels (Figure 12). This process results in a significant amount of the carbon in the original biomass being converted into a material with highly stable chemical structure, ie. biochar. When added to soil, high fertility and long-lasting carbon sequestration is the result, as shown in the *terra preta* soils created by indigenous farmers of the Amazon basin.

Biochar can remain in the soil for up to 5000 years.

When added to soil, nitrous oxide emissions can be reduced substantially.

However, there are issues that complicate the use of biochar as a beneficial soil amendment[107]:

- The effects of biochar on soil properties depend to a large degree on the type of feedstock used, and on the temperature and time of reaction. Biochars produced under certain conditions have been shown to have a detrimental effect on plant growth.

[102] Cartledge (2009)
[103] Kirkby (2009)
[104] Williams, Donald (1957)
[105] Cartledge (2009)
[106] Krull (2009)
[107] Krull (2009)

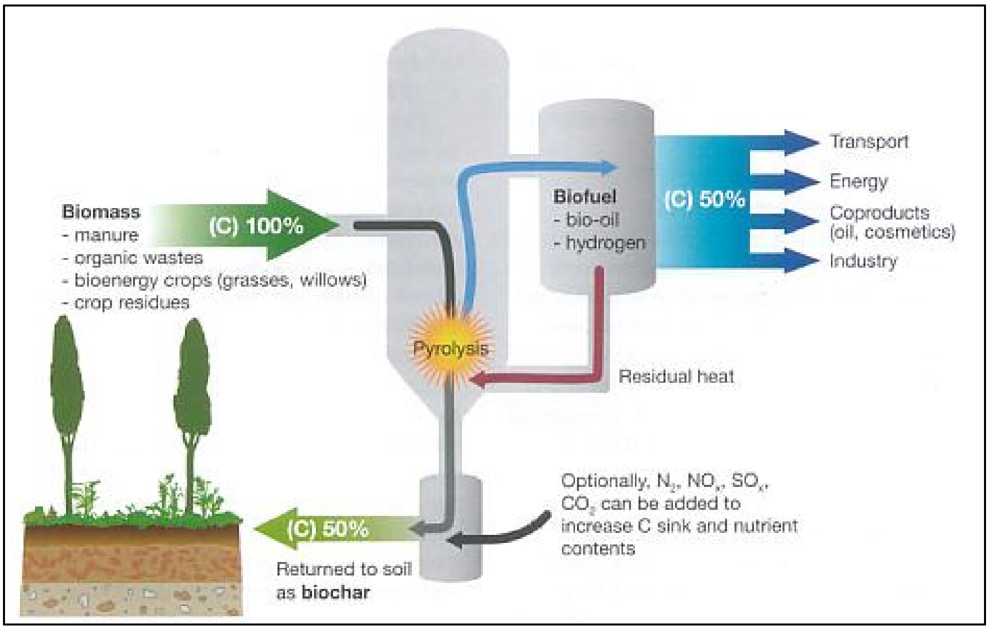

Figure 12 Concept of low-temperature pyrolysis bioenergy with biochar sequestration. Typically, about 50% of the pyrolysed biomass is converted into biochar and can be returned to the soil (Krull 2009).

- Not all soils respond positively to biochar applications. Most studies reporting positive effects have been on highly degraded and nutrient-poor soils, whereas application of biochar to fertile and healthy soils often yielded no change in the short term.

Biochar research priorities have been identified[108].

Dr Peter Grace

Peter Grace is Professor of Global Change at Queensland University of Technology, Brisbane.

He notes that increasing soil carbon is essential for sustainable agroecosystems and maintaining productivity and profitability[109]. However, Australia's generally high temperatures and variable rainfall limit the amount of biomass produced and lead to rapid degradation of what is produced[110]. Because of spatial variability in soil carbon across agricultural landscapes, verification costs are high. Therefore, soil carbon sequestration is likely to be non-viable as a carbon trading option.

Dr Grace believes that increased emphasis on mitigation strategies which have no permanence restrictions and no on-going verifications costs (eg. nitrous oxide reduction) may provide an easier and more effective method for Australian farmers to participate in carbon abatement schemes in the future.

108 Sohi *et al.* (2009)
109 Grace (2007)
110 Grace (2008)

7. Institutional arrangements – international, national, regional

CSIRO Land & Water is taking the lead internationally with the development of processes for reliable mapping, monitoring and forecasting of soil carbon. Dr Neil McKenzie made the following observations at a soil symposium that was part of the Copenhagen climate change meetings in late-2009[111]:

- Soil carbon management, in relation to climate change, is inter-connected with the need for soil scientists and their colleagues to increase food production globally by 75% over the next 40 years despite water scarcity, finite arable land, yield plateaux for major crops, increasing cost of management inputs and soil degradation.
- Bio-sequestration potential is large in many parts of the world, eg. degraded cropping lands, cleared grazing lands.
- Most soil spatial data are needed on a fine grid.
- Short-term project and program funding (<5 years) does not deliver enduring environmental information systems.
- Spatial prediction and monitoring of soil is technically complex. Technical capability in government agencies needs to be rebuilt. Field training and regional knowledge of landscapes is critical.
- General consensus exists on methods for digital soil mapping but few formal standards have been developed. Confidence in the carbon offset has to be balanced with the cost of verification.
- New technologies that are being integrated include fine-resolution remote-sensing (eg. gamma ray spectroscopy), digital elevation models and spectroscopic calibration for soil carbon.
- Permanent monitoring sites are important.

Much remains to be organised. For example, which government agency in Australia is responsible for working with industry groups such as Dairy Australia to develop practical action plans associated with soil carbon management? CSIRO's charter limits their staff to research work. Since the demise of Land & Water Australia in 2009, there is no federal agency to coordinate the integration and 'packaging' of soil carbon science with agribusiness initiatives such as BMP programs and whole-farm planning. There also is uncertainty about the legislative framework that will be developed at the international, national and regional level to deal with soil carbon assessment and management.

Other CSIRO initiatives

CSIRO's Soils and Landscapes Theme aims to produce a comprehensive Australian 50m resolution digital soil map[112]. It is now feasible to base the grid on a single digital elevation model which covers the continent, in conjunction with new spectral and geophysical remote sensing systems. This obviously will provide opportunities for the dairy industry.

[111] McKenzie (2009)
[112] Grundy (2008)

8. A summary for dairy farmers

The benefits of soil organic matter

Understanding soil carbon is important for anyone interested in the production of healthy food and in caring for the environment.

Apart from its capacity to offset carbon emissions associated with human activity, soil organic carbon has numerous other benefits for dairy farmers including:

- Stabilisation of soil aggregates – this reduces the risk of waterlogging under moist conditions and softens the soil when dry;
- Food for beneficial soil organisms;
- Slow-release source of nutrients;
- Increased water holding capacity, particularly in sandy soil;
- Increase in nutrient holding capacity by improving cation exchange capacity;
- Binding of toxic cations such as aluminium in a form that is unavailable for plants.

Potentially there may be an opportunity for farmers to make money from the sale of carbon credits when they capture carbon dioxide from the atmosphere and store it in their soil. Carbon prices are very low in early 2010, but increases are likely if international climate change agreements can be achieved and binding national targets set.

But is carbon sequestration achievable, affordable and low-risk for dairy farmers? As outlined below, the conclusion from this review of all the science is "almost certainly not".

Issues that make carbon sequestration an unattractive investment decision for dairy farmers

The carbon content of dairy soils often is excellent already - the scope for improvement is limited

Dairy farmers generally have a relatively high concentration of organic matter in their soil following application of best-practice soil management such as fertilisation, land application of effluent and improved pasture cultivars and limited cultivation. Also, they tend to be on the very best soil in a district – for example, basaltic soil of west Gippsland and south-western Victoria – so further improvements in soil condition are difficult to achieve.

Southern Australia is becoming hotter and drier

Southern Australia has become warmer over the last 50 years and many predict this trend will continue. A rise in soil temperature increases the rate at which existing organic matter decomposes. Studies in the UK and New Zealand have demonstrated country-wide declines in soil carbon content over the last 3 decades, possibly because of warming. The greatest losses occurred in soil with the highest initial organic matter contents.

It is ironic that the very problem we want to fix (increasing atmospheric temperature) is making the chances of success with soil carbon-related solutions increasingly difficult.

Reduced rainfall (through natural variation or climate change) reduces the ability of a site to produce enough vegetation to replace the declining organic carbon reserves. Despite enthusiastic pronouncements about the ability of mycorrhizal fungi to overcome this limitation, it does little to change the situation.

If cultivation is part of the pasture production system, or if increased cultivation is part of future dairy systems, the chances of accumulating soil carbon are reduced even further.

Nutrient tie-up in humus that is expensive to replace.

Even if cool wet seasons were to return, there is a challenge associated with the economics of 'carbon farming' because expensive nutrients are locked up in humus. The cost of fertilizer is likely to become greater over the 2010s and 2020s because of supply constraints. Phosphorus is a key driver of pasture productivity in southern Australia, but world supplies of phosphorus are becoming a major concern.

Carbon trading contracts

The signing of a carbon sequestration contract by a dairy farmer can be a two-edged sword. If soil carbon levels were to fall, this could lead to a situation where they have to pay the carbon trader for the 'loss', rather than the trader paying the farmer for the 'gain'. For example, an accidental loss of soil carbon in a drought, or the 'deliberate' loss of soil carbon via cultivation, would have to be restored through alternative management practices; otherwise emissions permits may have to be bought. If carbon prices become a lot higher in the near future, farmers could have to pay increasingly large amounts of money where soil carbon is inadvertently lost, unless protected by a soil carbon insurance policy, which would itself cost money.

Some of the potential risk factors are shown in Table 6.

Table 6. Risk assessment for soil carbon trading on dairy farms.

Risk factor	Relevance to dairy farmers in southern Australia
Permanence of the sequestered organic carbon	Landholders are unlikely to be able to prove that their soil carbon will last for at least 100 years as implied by the Kyoto protocol rules. The main exception is likely to be biochar, which has strong resistance to decomposition. However, the cost (mainly transportation) has to be carefully considered in relation to likely financial benefits of biochar to dairy farmers. In addition, it is likely to be the biochar 'manufacturer' who is likely to collect the carbon credits.
Additionality	Most dairy farmers already implement 'best management practice' for their pasture and soil management because it is so important for overall profitability. Therefore it will be difficult to demonstrate carbon-friendly soil management practices over and above normal good practice on dairy farms.
Measurability via independent audit	Soil carbon measurement is possible but expensive if small differences have to be proved and if gains in soil carbon have to be continuously verified. On the positive side, measuring soil carbon is not a futile exercise when part of a comprehensive topsoil-subsoil assessment process across a dairy farm.
Registration	Once the soil carbon is traded, farmers no longer own that carbon and contracts are likely to specify that the carbon must be protected for a long period of time or be 'repurchased' by the farmer. The soil carbon contracts represent a long term commitment connected with the land title. There is a loss of flexibility and potentially a long term liability.

Alternative approaches

The more severely degraded a block of land is, the greater the chances of success with carbon sequestration. In the unlikely event that severely degraded land were purchased for dairy farming, and then if the subsoil constraints were overcome and productive dairy pastures were established, there almost certainly would be a significant increase in soil carbon.

For example; a strongly compacted soil with poor shrink-swell capacity that is shedding most the rainwater that falls could be ameliorated in a cost effective fashion with agrowplowing at an appropriate moisture content and a pasture established.

If carbon sequestration became a major driver of dairy farm profitability, then dairy farmers could encourage plant breeders and research scientists to accelerate progress with some of the following:

- Develop deeper root systems for pasture plants which may access more soil water and nutrients, thereby increasing total carbon capture and perhaps deposit more of that carbon deeper in the soil where it is better protected from decomposition;
- Evaluate the viability of alley farming systems with strips of deep rooted edible shrubs, which could provide the same function as deeper rooted pasture species;
- Develop better water use efficiency for pasture plants so that despite declining water availability, total pasture production – and therefore soil carbon levels – might be increased;
- Investigate the incorporation of waxy materials and phytoliths (plant stones) in plant tissues that are slow to decompose in the soil, although the impacts of these carbon sources on the digestibility and palatability of pasture species would need to be minimised;
- Explore the economics of converting pasture/shrubs/trees etc into biochar on-farm.

Overall conclusions

Soil carbon is an essential component of all healthy soils. Management practices that boost pasture production tend to increase soil carbon levels and vice versa. However, because dairy pastures tend to have already built up more soil carbon than other types of farming, there is no guarantee of further increases in soil carbon under pasture in southern Australia – even it became a management focus – because of uncertainty about future climatic conditions.

The work of many leading soil scientists indicates that the potential for soil carbon sequestration to have a significant impact on Australia's carbon emissions has been over-sold and the greatest potential is in soils that have been highly degraded. In other words, there are likely to be few (if any) profitable opportunities for dairy farmers to obtain income from soil carbon sequestration.

The risks of failure appear to be less in schemes that reward the reduction in emissions of potent greenhouse gases such as nitrous oxide, for example through soil structure improvement. Similarly, there may be opportunities to reduce methane emissions (about 75% of dairy farm emissions are from enteric methane) but that is beyond the scope of this review.

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Appendix A. Contract (MCK13538) between Dairy Australia and McKenzie Soil Management Pty Ltd – Schedule A

1. THE SERVICES

There is an ongoing debate regarding the potential for carbon sequestration in agricultural soils. Dairy Australia wishes to better understand how the issues and the debate surrounding soil carbon sequestration might affect the dairy industry, and what opportunities and/or challenges might face dairy farmers.

This project is about pulling together the story of soil carbon in the grazing industries of southern Australia. There will be a dairy emphasis but there is unlikely to be sufficient research evidence from the dairy industry to develop a purely dairy based report. Likewise it is unlikely that there is enough Australian data from the grazing industries, so strong links to the international literature are essential.

This 'carbon story' needs to cover (this list is indicative rather than pre-empting the final report):

- The buildup and/or decline in the different carbon pools over time under grazing systems;
- The impact of management including management interventions such as grazing or cultivation on the soil carbon pools;
- The relevance of these carbon pools to the issue of sequestration and carbon trading and the potential opportunities for farmers to help meet national carbon reduction targets;
- An examination of the flow on effects from management changes that seek to increase soil carbon sequestration – these might include extra fertilise requirements, through to impacts on profit or even to other greenhouse gas emissions (eg Nitrous oxide);
- The impact of high soil carbon levels on nitrogen mineralisation rates and nitrogen fertiliser requirements (as experienced in SE SA)
- An examination of the challenges associated with increased soil carbon sequestration in grazing systems – these might include elements of the Government's intention (taken from Kyoto) that carbon offsets meet internationally accepted principles of permanence, additionality, measurability, avoidance of leakage, independent audit and registration.
- Across these and any other issues that arise during the conduct of the review, Dairy Australia is looking for a scientific evaluation of the positives and the negatives (ie we are not starting with a pre-conceived notion that soil carbon sequestration is inherently a good or a bad thing). In addition, were there is insufficient scientific evidence for real clarity, Dairy Australia is seeking for this review to reach 'informed conclusions' about the issues.

Outputs for project:

a) The only output from the project is a comprehensive report outlining all the evidence about soil carbon buildup/sequestration and decline as outlined above. There are many positives associated with soil carbon (independent of greenhouse gas issues) and many challenges. This report will explore both the positive and the negative issues for the grazing industries.