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A Review of Carbon Sequestration in Vegetation and Soils: options, opportunities and barriers for the Southern Slopes Cluster NRM organisations

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Executive Summary

Liz Hamilton, *Knowledge Broker, Department of Environment and Primary Industries, Victoria.*

This report was prepared by the Southern Slopes Climate Change Adaptation Research Partnership, (SCARP) specifically for the Southern Slopes Cluster of regional Natural Resource Management (NRM) agencies to assist them with their climate change impact and adaptation planning. The report focuses not only on ways of sequestering carbon in aquatic and terrestrial environments, but also ways of maintaining and preventing loss from existing stocks of stored carbon in the environment. Sequestration activities that reduce greenhouse gas (GHG) emissions in the Agriculture, Forestry and Other Land Use (AFOLU) sector, that are within the sphere of activities relevant to regional NRM agencies, are examined.

Carbon sequestration is the general term used for the capture and long-term storage of carbon dioxide (CO_2). The IPCC Working Group 3 identify three broad categories for mitigating GHG's in the AFOLU sector:

1. Reduction/prevention of emissions to the atmosphere by conserving existing carbon pools
2. Carbon Sequestration – enhancing the uptake of carbon in terrestrial reservoirs
3. Reducing CO_2 emissions by substituting fossil fuels and energy-intensive products with organic ones, (IPCC WG3 2014).

According to the Australian Soil Carbon Mapping project, the average amount of soil organic carbon (SOC) in the top 30 cm of Australian soil is estimated to be 29.7 tonnes per hectare. The largest SOC stores occur in the cool, temperate zones which have above average rainfall and extensive eucalypt forests and rainforests. These forest types occur in the Southern Slopes region in parts of Victoria and southern NSW as well as extensive areas of Tasmania. The amount of organic carbon in Australian soils varies significantly, from rainforests and well managed peat soils under pasture which can be >10 per cent, to <1 per cent on heavily cultivated soils.

There are no mitigation/sequestration practices that are universally applicable and effective in reducing GHG emissions in the land sector. Each agricultural system and associated land management practice needs to take into account climatic and edaphic parameters, current and historical patterns of land use and management, as well as their potential to create negative Indirect Land Use Change (ILUC) impacts elsewhere. Change in land management leading to increased carbon in soil or vegetation must be continued indefinitely to maintain the increased stock of SOC.

Conversion of agricultural land to woody vegetation will remove carbon from atmospheric CO_2. However, carbon farming, if not implemented carefully, can create dis-benefits such as increased land clearing, monoculture plantations replacing biodiverse remnants and unintended off-site impacts. Where conversion to woody vegetation results in a loss of agricultural land, it is often only considered to be a positive carbon sequestration activity suited to surplus agricultural land or land that is of marginal productivity.

Increased productivity on existing agricultural land could avoid ILUC impacts such as deforestation and its attendant emissions. However, as the carbon and nitrogen cycles are linked, increasing productivity through increasing inputs can inadvertently lead to increased emissions of the more problematic greenhouse gases, (GHG), methane and nitrous oxide.

Where opportunities exist for carbon sequestration on agricultural land, establishing new forests, grasslands or perennial shrubs, including perennial biofuel crops, on land of limited agricultural value is commonly cited as one of the better options for implementing a carbon sequestration program. Such areas would have minimal impact on food production, avoiding indirect land-use change, (ILUC) and could include:

- Polluted soils affected by past industrial activity
- Salt-affected soils
- Steep land with a large erosion and landslip risk
- Land that has become degraded for other reasons.

Various Australian studies, described later in this report, indicate that there are few areas where carbon forests in Australia are economically viable, even when a price on carbon pollution was in place. Given plausible scenarios for costs of establishment, discount rate etc., a carbon price of between $18-40/tonne may be required to make carbon farming (based on revegetation) financially viable. However, recent studies also indicate that young Mallee eucalypts and environmental plantings can grow and sequester carbon at much higher rates than previously estimated, particularly when grown in narrow belts with high stand densities and a high proportion of trees relative to shrubs. Environmental plantings, when well designed to deliver other benefits, may have an economic advantage over industrial plantations.

Most Australian studies have not accounted for changes in soil carbon under woody vegetation, which under-represents carbon sequestration. Current research is under development to better estimate and account for soil carbon under woody vegetation. Coinciding with this is the development of *Carbon Farming Initiative* (CFI) methodology, which is likely to lead to estimates of greater total carbon sequestration benefits under woody vegetation.

In Australia, there is considerable uncertainty about the potential of agricultural soils to store additional carbon, the rate at which soils can accumulate carbon, the permanence of this sink and how best to monitor changes in SOC stocks. Although there may be a strong theoretical basis for significant soil carbon sequestration potential in several Australian agricultural sectors, there are few field studies that unequivocally support this.

Results from south-eastern Australian field trials indicate that management practices such as fertiliser application, cultivation, stubble retention, crop rotations and grazing management appear to have relatively small or no effects on SOC stocks.

The greatest potential for soil carbon sequestration gains may come from land management shifts such as conversion from cropping to permanent pasture and retirement and restoration of degraded land. However, conversion from cropping to permanent pasture incorporating ruminant grazing, may result in a significant increase in methane emissions. Other *theoretical* options that show potential are:

- Large additions of organic materials such as green wastes and manures,
- Maximising pasture phases in mixed cropping systems, and
- Shifting from annual to perennial species in permanent pastures.

Adding organic materials such as crop residues or animal manure to soil may not constitute an additional transfer of carbon from the atmosphere to land, depending on the alternative fate of the residue. Sub-soil manuring may hold more promise as indicated by recent trials in high rainfall cropping zones in south-eastern Australia. Increases in SOC from reduced tillage may be smaller than previously claimed and in some situations may lead to increased N_2O emissions.

Biochar is an area of considerable interest for carbon sequestration due to its claimed ability to remain stable in soils for long periods and potential productivity benefits. To validate biochars' potential, a full life-cycle approach must be taken that considers all aspects of the biomass procurement and biochar production and application systems. Currently, there are few studies quantifying the net GHG emissions from actual biochar systems.

Increasing efficiency of nitrogen use in order to decrease N_2O emissions, may be a more significant and potentially manageable area to focus on to reduce GHG emissions from the agricultural sector.

Many researchers have noted that there are numerous benefits to be gained from increasing, and/or mitigating carbon losses from soil and permanent vegetation and conclude that carbon farming and soil carbon sequestration schemes should avoid a 'carbon-only' focus and that additional incentives may be needed to target soil carbon sequestration and tree establishment in areas which will have other environment benefits such as improved productivity and biodiversity outcomes.

Design of carbon farming incentive schemes should reflect overall public values and have local participation and buy-in on policy decisions if they are to have broad uptake and acceptance in regional communities. It is likely that, like carbon farming based on revegetation, soil carbon sequestration will need incentives before wide-scale adoption is seen.

Carbon stored in tidal marshes, mangroves, and seagrass beds, (blue carbon) is captured and stored up to 100 times faster than in forests and stored for thousands of years, hence sequestration of carbon via protection and restoration of these environments may be more economical than terrestrial carbon storage. Current estimates of blue carbon stocks and understanding of the processes responsible for sequestering the carbon are limited, although this is an active area of research both in Australia (through the CSIRO's Coastal Carbon Cluster) and overseas.

Terrestrial carbon sequestration options and their potential impact on soil carbon stocks and greenhouse gas emissions reduction are summarised in Appendix A.

The implications of a changing climate over coming decades must also be a key consideration of carbon sequestration programs. While potential exists for the landscape to store additional carbon, higher temperatures and increases to seasonal variability can introduce changed risk profiles to the carbon stored in our landscape. This requires stewardship and maintenance of current carbon reserves to be as much a priority as the effort to sequester additional stocks in the southern regions..

These reports are, or will soon be, available on the

CSIRO's Terra Nova website

Other reports in this series

SCARP has also produced the following reports which are, or will soon be, available on the CSIRO's Terra Nova website:

- *Southern Slopes Information Portal Report: climate change adaptation information for natural resource planning and implementation*
- *Adaptation Pathways: a playbook for developing options for climate change adaptation in Natural Resource Management*
- *A means-to-an-end: a process guide for participatory spatial prioritisation in Australian natural resource management.*
- *An Adaptive Capacity Guide Book: assessing, building and evaluating the capacity of communities to adapt in a changing climate.*

CSIRO and the Bureau of Meteorology also produced a technical climate report for the Southern Slopes Cluster:

Grose, M. et al., 2015, Southern Slopes Cluster Report, Climate Change in Australia Projections for Australia's Natural Resource Management Regions: Cluster Reports, eds. Ekström, M. et al., CSIRO and Bureau of Meteorology, Australia. Available at: http://www.climatechangeinaustralia.gov.au/en/publications-library/cluster-reports/

1. Carbon, climate change and greenhouse gas emissions in the agriculture, forestry and other

Carbon is an essential element of all living and dead organisms and is found in a vast array of organic and inorganic compounds on land, in soils and oceans and in the atmosphere. Every living organism needs carbon to sustain life whether for physical structure, or as an energy source, or both (VRO 2014). Carbon naturally exchanges between the atmosphere, terrestrial and aquatic systems in a set of equilibria over both short and long time cycles. A useful animation of the carbon cycle is provided on the Victorian Resources On-line (VRO) website (2014).

World-wide, the Agriculture, Forestry and Other Land Use, (AFOLU) sector is responsible for around 24% of anthropogenic, (human-induced) GHG emissions, mainly from deforestation and agricultural emissions from livestock, soil and nutrient management, (IPCC WG3 2014). In this report the IPCC estimate that around 22-24% of the total global GHG emissions are from agriculture; a combination of methane (CH_4) and nitrous oxide (N_2O).

The IPCC AR5 Working Group 3 identified opportunities for mitigating GHG's in the AFOLU sector as falling into three broad categories:

1. Reduction/prevention of emissions to the atmosphere by conserving existing carbon pools in soils or vegetation that would otherwise be lost, or by reducing emissions of N_2O and CH_4,
2. Carbon Sequestration – enhancing the uptake of carbon in terrestrial reservoirs, e.g., through management changes within the same land use type and consequential removal of CO_2 from the atmosphere; and
3. Reducing CO_2 emissions by substitution of biological products for fossil fuels or energy-intensive products (IPCC WG3 2014a)

1.1 Terrestrial environments as a source and sink of atmospheric carbon

Within the terrestrial biosphere, carbon can behave as a source or a sink for atmospheric CO_2 thus potentially mitigating or accelerating the rate of climate change, (Lal 2004 cited in Nuttall 2007). The carbon sequestration potential of terrestrial ecosystems depends on the type and condition of the system, that is, species composition, structure, and (in the case of forests) age distribution. Also important are site conditions, including climate and soils, natural disturbances, and management. It should be noted that current stores may change over time due to climate change itself. The likelihood of potential negative feedbacks that result in loss of CO_2 from terrestrial systems remain uncertain at all scales (IPCC 2007).

1.2 Terrestrial carbon stocks – above and below ground

Various, and widely differing, estimates of global carbon stocks are available. The IPCC provide an estimate of global terrestrial carbon stocks in their 4th Assessment report to a soil depth of 1 metre which includes both vegetation and soil carbon stocks, (IPCC, undated).

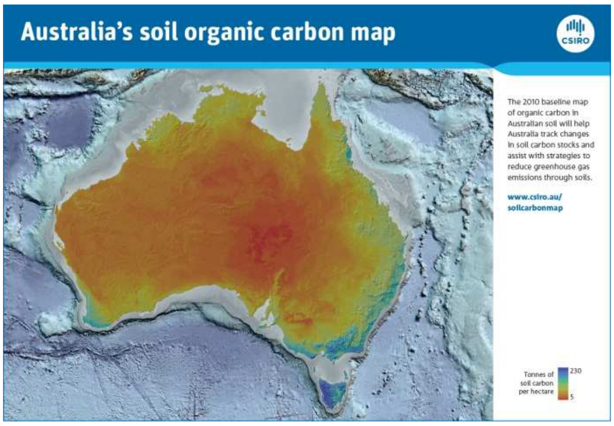
Haverd et al., (2012) undertook a construction of the full Australian carbon budget (1990–2011).

The CSIRO's, Australian Soil Carbon Mapping project provides national scale representation of SOC stocks. The authors (Viscara Rossel et al. 2014) concluded "the average amount of organic carbon in the top 30 cm of Australian soil is estimated to be 29.7 tonnes per hectare and the total stock for the continent at 25.0 gigatonnes (Gt = 1000 million tonnes) with a 95 per cent confidence of being within the range of 19.0 to 31.8 Gt." They estimated Victoria's soil carbon stocks to be 1.68 Gt with 95 per cent confidence of being within the range of 1.38- 2.02 Gt. Tasmania's soil carbon stocks are estimated to be 1.05 Gt with 95 per cent confidence of being within the range of 0.85- 1.27 Gt.

Figure 1.1 indicates that Australia's largest SOC stores per hectare occur in the cool, temperate zones, of south eastern Australia, which have above average rainfall and extensive eucalypt forests and rainforests (CSIRO 2014a). These soil and associated forests types occur in parts of the Otway Ranges, the Central

Highlands and East Gippsland as well as extensive areas of Tasmania.

Figure 1.1 The 2010 baseline map of organic carbon in Australian soil. Source: CSIRO Australian Soil Carbon Mapping. Extract from Viscarra Rossel (2014)



The 2010 baseline map of organic carbon in Australian soil will help Australia track changes in soil carbon stocks and assist with strategies to reduce greenhouse gas emissions through soils.

www.csiro.au/soilcarbonmap

The amount of organic carbon in Australian soils varies significantly, from rainforests and well managed peat soils under pasture which can be >10 per cent, whilst in poorer, or heavily exploited soils, levels are typically <1 per cent, (Robertson 2012, CSIRO 2011).

Norris et al. (2010) estimated the total above-ground carbon stocks on Victoria's publicly managed land to be 750 million tonnes (2750 million t CO_2). Their carbon accounting model (Fullcam) simulations showed that harvesting, wildfires and prescribed burns are major causes of change in carbon stocks on Victoria's publicly managed land and that the total Victorian carbon stocks are highly correlated with large-extent wildfire events; the effect of which is considered to be largely transient even when the corresponding emissions are significant. In Victoria, Mountain Ash forests, dominated by *Eucalyptus regnans* have the highest above – ground carbon stocks of the major Victorian vegetation types (Norris et al. 2010). Meaningful estimates of carbon stocks on privately managed land in Victoria are not available.

A 2012 estimate of the total area under 'carbon forests', i.e. vegetation planted to gain income from the carbon trading market in Australia suggests an area of just over 65,000 ha, 78% of which are either Mallee or mixed-species biodiversity plantings (Mitchell et al. 2012).

1.3 Defining carbon loss mitigation, carbon sequestration and additionality

For the purpose of this review, it is relevant to examine not only ways of *increasing, (sequestering)* carbon in terrestrial and aquatic soils and plants, but also *ways of maintaining and preventing loss* (*mitigation*) from existing stocks of stored carbon in these ecosystems.

Only activities that store carbon and/or reduce greenhouse gas (GHG) emissions, that are within the sphere of activities relevant to Catchment Management Authority, (CMA), Natural Resource Management, (NRM) and Local Land Services, (LLS) organisations in the Southern Slopes Cluster region of south eastern Australia shall be explored in this review. This includes carbon storage and emissions reductions in both the Agriculture, Forestry and Other Land Use, (AFOLU) sector and within aquatic 'blue carbon' ecosystems.

Soil carbon sequestration is commonly used to describe any increase in SOC content. This usually infers a change in land management and implies that increased soil carbon storage helps mitigate climate change. Genuine carbon sequestration results in an additional net transfer of carbon from the atmosphere to land (Powlson et al. 2011, IPCC 2014a). The Commonwealth Government, (2010) state that "Increasing input rates or decreasing loss rates of soil carbon can shift the soil carbon pool to a higher equilibrium and have other benefits including improved soil nutrients uptake, (where nutrients are available), water holding capacity and overall productivity".

Mitigation refers to avoiding emissions of greenhouse gases into the atmosphere, in the context of soil carbon. Decay or combustion of organic matter leads to CO_2 release and, in most cases, debate about emissions reduction centres on reducing use of fossil fuels which are long term stores of organic carbon. Large quantities of carbon are stored in Australian soils and vegetation; thus mitigating losses of carbon from these stores will be critical to ensure that large quantities of currently stored carbon are not released into the atmosphere, further Increasing GHG emissions. According to the IPCC report undertaken by Smith et al. (2007), a practice effective in reducing emissions at one site may be less effective or even counterproductive elsewhere.

Furthermore, the IPCC conclude that ‘‘there is no universally applicable list of mitigation practices; each practice needs to be evaluated for individual agricultural systems based on climate, edaphic conditions, social setting, and historical patterns of land use and management’’ (Smith et al., 2007, p. 499) (Note: the IPCC rate this statement as *high agreement, much evidence*).

Sequestration means stored for safekeeping. Carbon sequestration is the general term used for the capture and long-term storage of CO_2. Capture can occur at the point of emission (e.g. from fossil fuel combustion) or through natural processes (such as photosynthesis), which remove CO_2 from the earth's atmosphere and which can also be enhanced by appropriate management practices.

The carbon sequestration potential of terrestrial ecosystems depends on the type and condition of the ecosystem including its species composition, structure, and (in the case of forests) age distribution. Also important are site conditions, including climate and soils, natural disturbances, and management.

According to the Australian Government (2010) carbon sequestration methods include:

- “Enhancing the storage of carbon in soil (soil sequestration);
- Enhancing the storage of carbon in forests and other vegetation (plant sequestration);
- Storing carbon in underground geological formations (geo-sequestration);
- Storing carbon in the ocean (ocean sequestration); and
- Subjecting carbon to chemical reactions to form inorganic carbonates (mineral carbonation)”.

Note: This report will focus on carbon sequestration practices involving either the enhancement of existing, or development of new, carbon stocks sequestered either within vegetation or soils or a combination of both. Carbon sequestration (biosequestration) and emissions mitigation methods fall under three general categories:

- Changes in land use
- Maintenance or change in land management practices, and
- Addition of carbon to the land from external sources.

Additionality is a requirement under both the federal government’s Emissions Reduction Fund, (ERF) and the Carbon Farming Initiative, (CFI) where carbon credits units are issued for emissions reductions that are ‘additional’ that is, “they are not likely to have occurred under normal business conditions” (CFI Amendment Bill 2014, p.9). Current law provides for additionality in a number of ways, including the application of a common practice test. Under the new draft CFI Amendment Bill the common practice test is removed and replaced by a requirement that “projects must be new and unlikely to occur as a result of another government programme”. The existing criterion that projects must be additional to regulatory requirements is maintained.

A well referenced table of supply-side mitigation and sequestration options in the AFOLU sector is provided in IPCC Working Group 3 – Assessment Report 5 Chapter 11, pp. 23-25. The table outlines the various options and summarises their technical mitigation potential, ease of implementation (acceptance or adoption by land manager) and timescale for implementation (IPCC 2014a).

2. Terrestrial plant sequestration

'Carbon sequestration' is used to describe the capture and long-term storage of CO_2. The carbon sequestration potential of terrestrial ecosystems depends on the type and condition of the ecosystem, i.e. its species composition, structure and age distribution. Also important are site conditions, including climate and soils, natural disturbances and management.

Under Australia's Carbon Farming Initiative, Sequestration Offset projects are defined as those that:

> *"remove carbon dioxide from the atmosphere by sequestering carbon in living biomass, dead organic matter or soil; or remove carbon dioxide from the atmosphere by sequestering carbon in, and avoid emissions of greenhouses gases from, living biomass, dead organic matter or soil" (Department of Environment, undated).*

2.1 Plant sequestration options - positive and negative impacts

Afforestation and reforestation plantings can offer one of the more robust ways for the agricultural sector to sequester carbon and off-set GHG emissions because the carbon sequestered is generally measurable and verifiable (Polglase et al. 2011). 'Carbon farming' and other mixed-species plantings usually provide environmental benefits and public good benefits in addition to carbon sequestration. Such benefits may include biodiversity enhancement, shade, shelter for stock and crops from wind, salinity mitigation, pollination, carbon sequestration, and amenity value (Polglase et al. 2013; Polglase et al. 2011; Paul, 2013). They can be designed to be integrated into farming systems in ways that have no negative impacts and, possible positive impacts on agricultural production (Paul et al. 2013a).

Converting agricultural land to woody vegetation may also have negative Indirect Land Use Change, (ILUC) impacts (IEA Bioenergy Task 39, 2009; Powlson et al. 2011; IPCC, 2014). ILUC is a concept developed in relation to conversion of land from food crops to bioenergy feedstocks though it is applicable where land is removed for other non-food uses such as afforestation or revegetation (Powlson et al. 2011). ILUC which leads to reduced agricultural production within one region may in turn be offset by increased conversion of land, say from perennial native vegetation to agriculture, reducing or even negating the overall net sequestration benefit. This is unlikely to be an issue in jurisdictions which have well enforced native vegetation removal controls.

In southern Australia, plantations and carbon farming have led to concerns over potential impacts on the availability of land for agricultural production and on water security (Polglase et. al 2011). Carbon farming, if can result in negative impacts such as increased land clearing, monoculture plantations replacing biodiverse remnants, and unintended off-site impacts such as reduced run-off and stream flows. The impacts of large revegetation projects, which may include carbon farming plantings, need to be considered at different scales and lifecycle analysis of different options may need to be undertaken to determine the most appropriate type and scale of planting (Polglase et. al 2011).. The IPCC note that frameworks designed to assess environmental or ecosystem services may assist with the evaluation of multiple benefits and trade-offs arising from mitigation actions (IPCC 2014a). Carwadine et al. (2015) provide an approach for assessing opportunities and spatial priorities for carbon sequestration and biodiversity restoration through biodiverse carbon plantings in Australia.

Lin et al. (2013) recommend carbon farming schemes avoid a carbon-only focus, considering co-benefits of revegetation also. They also concluded that schemes that have local participation and buy-in on policy decisions that reflect overall public values, are more likely to be successful over the long term than those focussed just on the interests of private landowners. Important considerations associated with designing practical market-based instruments that offer maximum benefits with minimum impacts are discussed by Lin et al. (2013), providing a useful guide for organisations looking to avoid potentially perverse NRM outcomes from carbon market schemes.

Various Australian studies into the economic and social aspects of revegetation-based carbon sequestration activities have been undertaken in recent years (Polglase et al. 2009, 2011, 2013; CSIRO, 2009a; Paul et al. 2013a; Flugge et al. 2006). The results of these are diverse and very much dependent on the scenario and assumptions used in the modelling, for example, the discount rate, the cost of land and the price on carbon.

2.2 Restoration of degraded and marginal lands

The IPCC note that where land use conversion comes at the expense of lost agricultural productivity, it is usually only considered as a positive carbon sequestration option suited to surplus agricultural land or land that is of marginal productivity (Smith et al. 2007). Re-vegetating degraded or surplus land of limited value for food production may avoid many of the issues discussed above. Establishing new forests, including perennial biofuel crops if they can be successfully grown on degraded land or land of limited agricultural value, is frequently cited in most of the above-mentioned reports as one of the better options long-term options for implementing a carbon sequestration program. Such areas would potentially have minimal impact on food production and avoid ILUC and could include:

- Polluted soils affected by past industrial activity;
- Salt-affected soils;
- Steep land with a large erosion and landslip risk; and
- Land that has become degraded for various reasons (Powlson et al. 2011). For example, outcompeting heavy weed infestations on steep lands (serrated tussock, gorse, blackberry etc).

2.3 Accounting for soil carbon sequestration under revegetation

Although there is considerable interest in afforestation and reforestation plantings in the agricultural sector to sequester carbon and off-set GHG emissions, the ability to accurately model the whole extent to which revegetation may increase *total carbon stocks* has been hampered by the lack of data available on soil carbon changes under revegetation (Paul et al. 2013). Consequently, participation in CFI reforestation projects currently only includes carbon sequestered in debris and biomass, i.e. possible carbon credits from additional soil carbon sequestration are from the carbon accounting process. This has required the development of a sound carbon accounting methodology, including the ability to understand and model changes in soil carbon following land use change (Paul et al. 2011a). Paul et al., (2013) undertook a study into 'Improved estimation of biomass accumulation by environmental plantings and mallee plantings using FullCAM'.

An endorsed CFI Methodology is under development; 'Methodology for Quantifying Carbon Sequestration by Permanent Mixed-Species Native Environmental Plantings or Permanent Mallee Plantings Using the Full Carbon Accounting Model'. FullCAM is used as part of the Australian National Inventory System to estimate greenhouse gas emissions and removals in the land sector. FullCAM provides fully integrated estimates of biomass, litter and *soil carbon pools* in forest and agricultural systems.

2.4 Environmental plantings and 'carbon plantings'

A number of studies suggest that Mallee eucalypts as a biomass tree crop can be profitable by enabling farmers to diversify revenue risk through provision of biomass and sequestered carbon to relevant markets - where available (CSIRO 2009a, Paul et al. 2013a). Within appropriate agro-climatic zones and soil conditions Mallee eucalypts can be integrated into farms with minimal interruption to existing operations of livestock and cropping enterprises (Farquarson et al. 2011). However, the evidence for the economic benefits of carbon farming with Mallee is equivocal.

Current research being undertaken by CSIRO, suggests that young Mallee and environmental plantings may sequester carbon at much greater rates than previously estimated (Paul et al. 2013a). Highest rates of carbon sequestration in young stands were found in narrow belts with high stand densities and a high proportion of trees relative to shrubs. Twenty-six discrete types of plantings were categorised providing a basis for calibration of FullCam. This project focused on Mallee and environmental plantings as these types of plantings;

1. are the most common types of new tree plantings established for carbon sequestration in medium-low rainfall regions where relatively low land values make such revegetation more viable, and
2. have a role in providing other environmental benefits and public good outcomes over and above carbon mitigation (Paul et al. 2013a). For example reducing erosion and subsequent carbon loss.

Further study into soil carbon under environmental plantings is due to be completed in 2015, (Paul, pers. comm. 2014). A summary of key projects around the theme of soil carbon under environmental can be found at the federal Dept. of Agriculture website, (DoA, 2014).

Furthermore, Paul et al. (2013a) examined the economics of three case studies (two farm forestry and one biodiversity planting) and found significant variation in economic viability both between and within case studies due to differences in site quality, management regime and planting layout and design. The authors concluded that the carbon price required for economic viability on marginal land sites are <$18t CO_2-e, even where the relatively high discount rate of 8% is used. They also conclude that any jobs generated from use of this low productivity land for carbon forestry would be additional, assuming that, (being marginal land) other agricultural land use options are unviable. Three-four row belt farm forestry plantings were generally the more economically viable, particularly in higher rainfall areas. They also concluded that supplementary payments may be needed to make biodiverse environmental plantings competitive in areas of lower, less profitable rainfall areas.

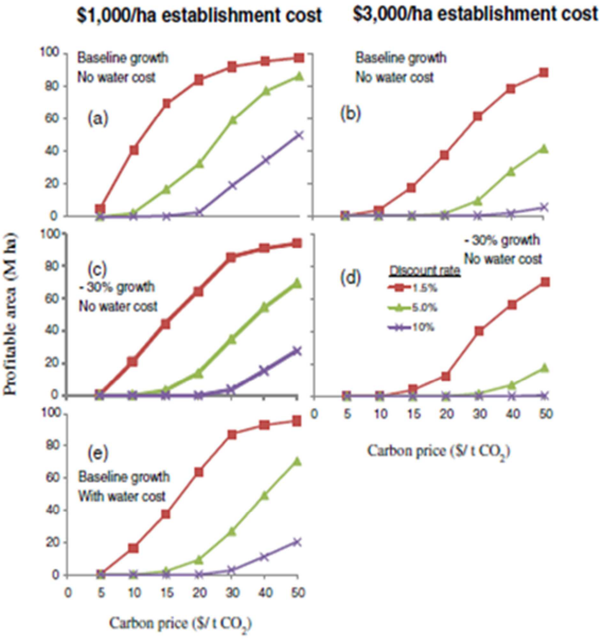
The potential for agroforestry for carbon sequestration and dryland salinity reduction was studied in low and medium rainfall salinity impacted regions in Western Australia (Flugge et al. 2006). Even after accounting for salinity benefits, the study concluded that the price of carbon would need to be A$25-A$46/tCO_2-e higher than expected to make growing trees a worthwhile investment. The 'expected' carbon price was set at $15/t$CO_2$-e. Western Australian research has also shown that competition for water and nutrients between Mallee trees and crops may present a significant cost to farmers and need to be considered in the design of integrated Mallee agroforestry systems (Sudmeyer 2012).

Carbon plantings can help offset GHG emissions and improve landscapes but it should be viewed as a long-term project in which co-benefits such as improved biodiversity need to be realised. From their modelling work Polglase et al. (2013) suggest that on average 1 million hectare (ha) of carbon forests established would offset about 1.4 % of Australia's year 2000 emissions (or 7.4 Mt CO_2/year) once an average rate of sequestration per ha was reached. They stated that "all studies that predict large areas of potentially profitable land for carbon forestry need to be tempered by the realities that constrain land use change" (Polglase et al. 2013 pp 162)

Polglase et al. (2011 and 2013) studied the potential for environmental carbon plantings to offset GHG emissions in Australia considering a range of social and economic factors. Varying discount rates, carbon prices, rates of carbon sequestration and costs for plantation establishment licenses for water interception were modelled across 105 scenarios. The authors concluded that no areas were identified as profitable until a carbon price of AUD$40 t CO2/year was reached - assuming the most plausible assumptions for cost of establishment and commercial discount rates. They also concluded that additional incentives may be needed to target tree establishment in areas which will have other environmental benefits such as biodiversity, and that in most cases it would take decades for new plantings to have a significant impact on emission reductions due to many practical constraints around plantation establishment. The impact of changing carbon price and discount rate on profitability are illustrated in Fig 2.1.

Furthermore, where carbon plantings are likely to be more economically viable, other land uses are also likely to outcompete them. For example, trees would grow well on deep fertile soils in high rainfall areas of Tasmania, but they may have to compete with other, more profitable, alternative land uses.

Figure 2.1 The impact of changing carbon price and discount rate, (1.5, 5 and 10%) on profitable area for two establishment costs, two growth rates and two water cost scenarios, (Polglase et al. 2011 pp.13).



A CSIRO (2009a) scoping report ‘*An Analysis of Greenhouse Gas Mitigation and Carbon Sequestration Opportunities from Rural Land Use*’ focussed on the GHG sequestration/mitigation potential likely to be achieved through land use change in Queensland (and in a broader Australian context). Each of the options detailed in the rural land use section of the Garnaut Climate Change Review (2008), were analysed to estimate the quantity of GHG sequestration/mitigation offered over a 40 year period, including risks and uncertainties associated with these estimates, to provide an assessment of the relative viability of each option. Economic, social, regional and institutional influences for each option were also considered. Biochar and biodiversity plantings options were also analysed. The analysis included an assessment of biological, technical and implementation uncertainty for each option. Although this study focussed on Queensland, many of the findings are relevant to south eastern Australia. As stated in this report, the following five factors were considered most likely to either contribute to the delivery of a final benefit or create barriers:

1. Maturity of science and technology - are technical solutions currently available to enable the option to be implemented?
2. Measurement feasibility - are there reliable and cost effective means of measuring GHG sequestration / mitigation?
3. Ease of implementation - are there existing models for implementation?
4. The net benefit of co-effects - are there well defined co-benefits or trade-offs associated with the option?
5. System stability / certainty into which the options would be applied - how variable are the natural systems into which the option will be applied? How well are these systems defined and understood?

The more favourable options which emerged from the analysis are explored further in the CSIRO report. Note, however, that the authors considered this to be a preliminary scoping report to inform future research directions, rather than an exhaustive analysis. Nevertheless, carbon forestry appeared to be the best option, followed by regrowth and plantations which had similar ‘ratings’ but decreasing quantity of GHG sequestration. Soil carbon sequestration under cropping, delivered the lowest GHG abatement and was rated as moderate for ease of implementation. Soil carbon changes associated with land use change (crop to pasture, pasture to trees) were not included in this report. The authors estimate the attainable GHG sequestered/mitigated for each option (for Queensland) plotted against the overall rating for complexity of implementation attributes (CSIRO 2009a pp. 26).

2.5 Forestry, industrial and bioenergy plantations vs environmental and ‘carbon plantings’

According to the 5th IPCC report on climate change mitigation, the most cost-effective mitigation options in forestry are afforestation, sustainable forest management and reducing deforestation, though regional influences affect the relative importance of each considerably (IPCC 2014).

Polglase et al. (2008) prepared a spatial framework for identifying areas of opportunity for various types of revegetation systems in Australia, including harvested tree plantations, (pulp sawn timber and bioenergy crops) and non-harvested carbon plantings. The study indicated that harvesting contributed up to 50% of the cost of the total harvested system, and that broader and more dispersed areas in the landscape are available to carbon plantings (since they don't need to be established near processing facilities). Dispersed planting also help avoid potentially negative impacts that large plantings can have on water resources. Furthermore, carbon embedded in harvested wood products is not currently included in Australia's carbon accounting methodologies. They concluded that compared to industrial plantations, carbon farming may have a potential economic advantage due to there being no associated harvesting costs.

Under current CFI accounting rules, (which excludes carbon in wood products and soil under forests) establishment of new industrial plantations are generally not economically viable without a carbon payment of about \$10–30 t CO_2-e (Paul et al. 2012a). Even higher payments may be required to make extending rotation lengths, to increase the amount of carbon sequestered economically viable (Paul et al. 2012a).

Bioenergy generated from agricultural, plantation and forestry crops and residues can be used to displace fossil fuels. Although bioenergy is generally beyond the scope of this review, it is worth noting the IPCC's recent interest in the climate change mitigation potential of bioenergy. The latest IPCC AR 5 WG 3 Report states that ''bioenergy could play a critical role for climate change mitigation, if conversion of high carbon density ecosystems (forests, grasslands and peatlands) is avoided and best-practice land management is implemented (robust evidence, medium agreement)", (IPCC, 2014a, pp 6). However, there are issues to consider such as the sustainability of practices and the efficiency of bioenergy systems. Harvesting for bioenergy should lead to a decrease in SOC, (relative to longer sawlog/pulpwood rotations) where bioenergy harvest cycles are relatively short, e.g. short rotation crops (IPCC 2014a; Paul pers. comm. 2014).

Removal of agricultural and forest residues has mitigation benefits, but the trade-off with removal of carbon from the ecosystem and impact on soil health, additional fertiliser input etc., needs to be quantified (IPCC 2014a).

A system of using farm forests to provide biomass for bioenergy generation, where the bioenergy plant incorporates carbon capture and storage via geo-sequestration - is a possible approach to achieving net CO_2 drawdown from the atmosphere whilst delivering economic benefits (European Technology Platform 2012).

2.6 Engaging landholders and communities in carbon farming

Bull and Schirmer (2012) studied attitudes and the willingness of NSW farmers towards planting trees for carbon sequestration under different scenarios. Their study found that the 'hobby' or 'lifestyle' property landholders were more likely to be interested in planting trees for carbon sequestration than landholders who manage their land primarily for agricultural production. Their report also indicated that the barriers to carbon tree plantings are mostly due to the size and design of the planting activity, and the importance of establishing reliable and trusted markets and engaging with landholders through extension efforts. The authors concluded that failure to address these barriers will lead to a substantial proportion of landholders unlikely to be willing to adopt carbon farming.

Lin et al. (2013) concluded that policy incentives need to be carefully constructed to encourage carbon plantings that deliver both public and private co-benefits that balance both objectives in order to incentivize the sustainable, long-term management of carbon plantings across the landscape.

Experience from various pilot carbon farming schemes have also demonstrated a number of issues which farmers see as potential barriers to adoption (DPI 2012; Graeme Anderson pers. comm. 2014), including:

- the nature of long term agreements that require attachment to land titles
- the scale of carbon required to make a carbon project viable
- the up-front costs from vegetation establishment, carbon accounting and legal services which are experienced long before any carbon income is realised
- the issue of intergenerational equity and how long term agreements might restrict future landowners to use the land or change land-use as they may wish (e.g. to meet changing markets)
- implications of carbon loss events such as droughts and fires, and options for future project termination or make good provisions (possibly when future carbon prices are much higher)
- how mortgage holders, banks or lessees respond when their consent is required for long term carbon agreements relating to property titles
- implications of effect of carbon agreements on land asset value and perceptions of future buyers.

3. Terrestrial soil sequestration

The global SOC pool is estimated to be 1580 Gt, which is twice as large as that in the atmosphere and nearly three times that of the vegetation biomass carbon pool (Chan et al. 2008). This is a key reason why carbon sequestration in soils is considered as a potential strategy for mitigating climate change.

In a CSIRO review of soil carbon sequestration potential in Australian soils, Sanderman et al. (2010 pp. v) concluded that ''There is a strong theoretical basis, partially supported by a limited number of field studies, for significant soil carbon sequestration potential in several Australian agricultural sectors''.

3.1 Australian soil carbon stocks

Baldock (2011) identified four biologically significant fractions of SOC. The amount of each type of organic carbon in Australian agricultural soils varies significantly. Labile carbon is released to the atmosphere as CO_2 through decomposition and microbial activity and has a relatively high turnover rate (<5 years) (Commonwealth government 2010). The amount of organic carbon in Australian agricultural soils varies significantly, from peat soils under pasture where the organic carbon content can be greater than 10%, to heavily cultivated soils, where the levels are typically less than 1% (Robertson 2012).

Accurately measuring soil carbon and statistically verifying changes in SOC stocks is complex due to the diversity of factors which affect SOC sequestration, such as changes in the type and quantity of vegetation cover and heterogeneity in soil environments and seasonal conditions (Sanderman et al. 2010; Baldock 2007). Various Australian studies have noted that there is a general lack of research in this area making it difficult to make definitive assessment of the sequestration potential of agricultural soils (Vic ENRC (2010; Sanderman et al. 2010). However, in recent times, a number of new studies have commenced within Australia, around the potential of agricultural soils to store additional carbon, the rate at which soils can accumulate carbon, the permanence of this sink, and how best to monitor changes in SOC stocks (see section below - *Other relevant terrestrial carbon sequestration research in Australia.* The Soil Carbon Research Program, (SCaRP) is an Australia-wide soil carbon research program involving researchers from federal and state government agencies and universities. The program is collecting information on soil carbon stocks, including studies around the potential of agricultural soils to store additional carbon, the rate at which soils can accumulate carbon, the permanence of this sink, and how best to monitor changes in SOC stocks. The information gained from these studies is aimed at underpinning Australia's carbon farming and sustainable agriculture systems, including GHG accounting and methodology development, through 13 projects across Australia.

3.2 What influences soil carbon sequestration and mitigation of loss?

The CSIRO explain carbon in soils as a 'leaking bucket', in constant need of topping up; the size of the bucket representing the amount of carbon the soil can potentially hold (CSIRO 2011). Soil carbon levels are influenced by many factors, including:

- Soil and vegetation type, which determines the carbon-holding capacity,
- Climate, especially rainfall and temperature which determine the rate of decomposition, and
- Land management practices, both current and historic (CSIRO 2011).

Soil carbon is in a constant state of flux; responding to inputs of organic matter, loss through grazing, decomposition and mineralisation from microbes and other soil fauna which convert carbon to CO_2. Changes in soil management that reduce input rates or increase loss rates may mean that the carbon pool size changes (CSIRO 2014b). Prior to the introduction of agriculture in Australia, our SOC levels were more or less in a state of equilibrium. Land clearing and conversion to agriculture has led to a decline in SOC across much of Australia and it is likely that many of these soils are still responding to the initial cultivation, and subsequently are still in a state of soil carbon decline (Chan et al. 2010; Sanderman et al. 2010; Luo et al. 2010). Across the Australian wheatbelt, it has been estimated that over 60% of SOC has been lost from the top 10 cm of soil, suggesting that there may be opportunity for extra soil carbon sequestration (Chan et al. 2010).

SOC can be maintained or increased by increasing organic carbon inputs or by reducing organic carbon losses. Processes that accelerate decomposition or erosion will accelerate the rate of soil carbon loss; the rate of loss being influenced by the:

- type and amount of organic matter, both plant and animal, entering the soil
- management practices which reduce carbon inputs, increase erosion and/or increase the decomposition of soil organic matter, including; fallowing, cultivation, stubble burning or removal and overgrazing
- climate conditions (rainfall, temperature, sunlight). For example, soil microbial activity increases with soil moisture and temperature; increasing average temperatures due to climate change may be expected to increase the turnover rate of labile carbon in soils, (Australian Government website, undated)
- soil properties, including the clay, silt or sand content (CSIRO 2011).

3.3 Effectiveness of agricultural management practices to sequester soil carbon and mitigate losses

Most of the carbon that enters soils does so as plant residues (Baldock 2007). Improving SOC levels can be achieved by either increasing organic carbon inputs or decreasing organic carbon losses. Land management practices that enhance productivity and the return of plant residues (shoots and roots) to the soil are likely to lead to an increase in soil carbon, though, as will be discussed below, any such increase may be short-lived, or difficult to detect for many years (Sanderman et al. 2010; Chan et al. 2010; Robertson and Nash 2012). Fire can also lead to an increase in soil carbon by converting organic matter into charcoal which enters the recalcitrant fraction. However, fire also leads to carbon losses through the process of combustion (CSIRO 2011).

The CSIRO (Sanderman et al. 2010) undertook a worldwide review of peer-reviewed studies of traditional management practices used to sequester soil carbon and concluded that: ''Within an existing agricultural system, the greatest theoretical potential for [soil carbon] sequestration will likely come from large additions of organic materials (manure, green wastes, etc), maximising pasture phases in mixed cropping systems and shifting from annual to perennial species in permanent pastures. Perhaps the greatest gains can be expected from more radical management shifts such as conversion from cropping to permanent pasture and retirement and restoration of degraded land. Other theoretical options that show potential are:

- large additions of organic material such as green wastes and manures
- maximizing pasture phases in mixed cropping systems, and
- shifting from annual to perennial species in permanent pastures''(Sanderman et al. 2010 pp. iv).

Chan et al. (2010) identified ways of improving SOC levels as follows:

SOC can be increased (sequestered) by:

- increasing crop yield
- optimising rotations to increase carbon inputs per unit land area,
- stubble retention
- increasing the amount of pasture grown
- returning manure and other organic materials to soils.

SOC losses can be reduced (mitigated) by:

- reducing tillage
- minimising stubble burning
- minimising periods of fallow
- reducing erosion
- avoiding overgrazing.

Chan et al. (2010 p 12) give estimates of average SOC sequestration rates relating to various agricultural practices, in *A farmers guide to increasing soil organic* *carbon under pastures*. They note that sequestration rates vary both between, and within, management practices and are generally less than 1 tonne of carbon/ha/yr averaging around 0.3 tonne of carbon/ha/yr.

3.4 Constraints, barriers and limitations to soil carbon sequestration

A variety of management practices can, in theory, slow the rate of soil carbon loss and/or increase soil carbon levels. However, in practice, it should be noted that because of the limitations on plant dry matter production and decomposition rates due to both soil properties and environmental conditions, there are specific levels of soil organic matter (SOM) that can be achieved for any farming system in a particular geographic region and soil type, (Baldock 2011; Powlson et al. 2011). Baldock (2007 pp 8.) also predicted that ''A pasture shoot dry matter production of more than 25 t/ha would be required over a 10 year period to double the soil carbon content of a site where the average annual yield of limed and fertilised pasture was 6.7 t/ha''.

Whilst most studies conclude that management options that increase SOC usually increase overall farm productivity, profitability and sustainability (Chan et al. 2009; Vic ENRC 2010; Sanderman et al. 2010) most of these of studies have also noted that management strategies aimed at increasing soil carbon may potentially lead to negative impacts as a consequence of the close linkages that exist between soil carbon and nitrogen cycles, and that this is an area requiring significant research (Barlow et al. 2011; Vic ENRC, 2010; Sanderman et al. 2010; MacEwan 2007). For example, changing from annual crops to permanent pastures may increase SOC, but it may also lead to an overall increase in total emissions where pasture is being used for ruminant livestock production.

Lam et al. (2013) quantitatively synthesised results of Australian studies using meta-analytic techniques to assess the technical and economic feasibility of increasing the soil carbon stocks by improved management practices, (conservation tillage, residue retention, use of pasture and nitrogen fertiliser application). Their results indicate that the potential of these improved practices to store carbon is limited to the surface 0–10 cm of soil and diminishes with time. The authors concluded that ''None of these widely adopted practices are currently financially attractive under Australia's Carbon Farming Initiative, (CFI)'', (Lam et al. 2013 p.1). Similar findings have been reported in other Australian studies (Kragt et al. 2012).

Increasing productivity in existing croplands could avoid deforestation and ILUC impacts and hence GHG emissions. However, maximising efficiencies and/or increasing productivity through irrigation and/or fertilization do not necessarily infer that soil carbon stocks will increase, due to the potential trade-off between increased C return to soil and increased decomposition rates (Robertson 2014; Sanderman et al. 2010). Lam et al. (2013) also concluded increasing the soil carbon stocks by improved management practices, may result in carbon markets generating new negative environmental externalities.

The Victorian Environment and Natural Resources Committee (2010) undertook a comprehensive Parliamentary Inquiry into Soil Carbon Sequestration in Victoria, (examining most aspects of soil carbon sequestration in Victoria). The enquiry, which engaged many of Australia's leading soil, climate and agricultural scientists, concluded that there are various agricultural and environmental benefits associated with soil carbon sequestration, including improved soil health, agricultural productivity, biodiversity and water quality outcomes. The enquiry also identified considerable risks and challenges associated with the measurement of soil carbon and participating in carbon trading and noted that some soil carbon sequestration practices may have adverse agricultural impacts and questionable economic benefits.

Other key considerations which may impact on the potential of soils to maintain and/or sequester soil carbon in the 'land sector' are as follows:

1. Genuine carbon sequestration should result in an additional net transfer of carbon from the atmosphere to land, not just movement of a carbon source from one site to another (Powlson et al. 2011; IPCC 2014a) - this may be of consequence

to farmers intending to participate in greenhouse gas reduction activities or schemes such as the Carbon Farming Initiative.

2. Accurate measurement of soil organic matter and statistical verification of changes in SOC stock is complex involving many factors affecting SOC sequestration, such as changes in vegetation cover and variability in soil environments (Baldock 2007; Sanderman et al. 2010).
3. There is a strong theoretical basis, partially supported by some field studies, for significant soil carbon sequestration potential in several Australian agricultural sectors (Garnaut 2008; Sanderman et al. 2010). However, there is a general lack of research in this area to allow for a more definitive assessment of the sequestration potential of agricultural soils (Robertson and Nash 2013; Sanderman et al. 2010). Inconclusive results may result from a number of factors including an inability to detect change (methodology/insufficient power of statistical tests), the age of the trial (particularly if the trial is less than 5 years old), and the environmental conditions at the site (e.g. rainfall and seasonal variability, clay content of soils) (Lam et al. 2013; Robertson and Nash 2013; Sanderman et al. 2010).
4. Soil carbon occurs in a number of different forms, each form having different vulnerabilities to, and rates of decomposition. Some carbon forms may are very quickly decomposed in the soil and are subsequently released back into the atmosphere as carbon dioxide, resulting in only transient carbon sequestration (CSIRO 2011; Baldock 2007).
5. The capacity for soils to sequester carbon is finite and there are specific maximum equilibrium levels of soil organic matter that can be achieved for any farming system due to the climatic and edaphic limits on plant dry matter production and decomposition rates, (CSIRO 2011; Powlson et al. 2010).
6. When management practices change, soil carbon can be readily released into the atmosphere. Future changes in soil management that reduce carbon input rates or increase loss rates may mean that the carbon pool size changes. Changes in land management leading to increased C in soil or vegetation must be continued indefinitely to maintain the increased stock of SOC (Powlson et al. 2010; Sanderman et al. 2010).
7. Increasing carbon input rates or decreasing loss rates of soil carbon can shift the soil carbon pool to a higher equilibrium and have other benefits including improved soil nutrients uptake, (where nutrients are available), water holding capacity and overall productivity.
8. In Australia, some management practices may only be reducing losses of C and not actually sequestering additional atmospheric carbon as a likely result of these soils still responding to the initial cultivation of the native soil and subsequent soil carbon decline (Sanderman et al. 2010; Luo et al. 2010).
9. An effective practice for reducing emissions at one site may be less effective or even counterproductive elsewhere. For example, shifting from cropping to pasture, without any decrease in market demand for crops, will likely lead to other land being put into cropping, merely transferring SOC losses to another farm, (IPCC 2014a; Powlson et al. 2011).
10. SOC can function as a significant source of nutrients for farm production, however, it is important to also consider the reverse of this process; increasing soil carbon [levels] will also require nutrients to be locked away and bound up along with the sequestered carbon. (Grace et al. 2015 ; Kirby et al. 2011)
11. Numerous studies have noted that management strategies aimed at increasing soil carbon may potentially lead to perverse impacts as a consequence of the intimate linkages that exist between soil carbon and nitrogen cycles, and that this is an area requiring significant research. For example, changing from annual crops to permanent pastures may increase SOC, but may also lead to an overall increase in total emissions where pasture is being used for ruminant livestock production. The benefit or otherwise will likely depend upon the specifics of the land management practice change.

12. Climate change may reduce the ability of soils to sequester carbon.

The benefits and limitations of both traditional land management practices and practice changes are considered below and summarised in Tables 1,2, 3 and 4 in Appendix A at the end of this report.

3.5 Practice options and evidence for grazing systems

Most Australian studies indicate that there is limited or no effect of management (grazing management, pasture improvement, pasture cropping, grazed woodlands) on total soil carbon, (Robertson 2012; DAFF 2013; CSIRO 2009a).

In temperate regions, the type of pasture grass grown may influence soil carbon levels, e.g. the SCaRP project no 8. which suggested SOC increasing under kikuyu but not under panic or Rhodes grass, although the authors felt that the soil type of the pasture is likely to be a key contributor to the long-term stability of the newly sequestered carbon.

3.5.1 Grazing management

Overgrazing has been a major cause of land degradation in Australia particularly under traditional continuous grazing systems and there is strong evidence that overgrazing can lead to erosion and subsequent loss of nutrients and carbon, as well as soil compaction, reducing the productive capacity of pasture systems (Chan et al. 2010; Robertson pers. comm. 2014). Overgrazing, that leads to the replacement of productive species with weed species, can also increase the likelihood of carbon loss through erosion. Chan et al. (2010) give the example of capeweed which is less-productive and rapidly dies off in late spring leaving bare areas, prone to erosion.

Rotational grazing systems have potential to increase biomass production over time, leading to higher soil carbon levels. However, the evidence for rotational grazing and other practices leading to an increase in SOC, including reduction of stocking intensity, grazing duration, set stocking rates etc. is equivocal or non-existent, (CSIRO 2009a). Though it is likely that grazing management practices that reduce the size of frequency of bare patches and reduce the extent of compaction will reduce erosion and hence carbon losses.

SCaRP project no. 7, which investigated the soil carbon levels in cropping and pasture systems of central and northern NSW, indicated limited or no effect of management (grazing management, pasture improvement, pasture cropping, grazed woodlands) on total soil carbon.

3.5.2 Pasture cropping

Pasture cropping involves direct drilling of winter cereal crops into predominantly summer-growing native perennial pastures, a technique first developed in central-west New South Wales (Chan et al., 2010). Theoretically, this system has potential to restore or enhance SOC more than that of conventional ley/crop systems, particularly in degraded pastures. However, there is little scientific data available to support the theory (Chan et al. 2010).

3.5.3 Native v. sown pastures

There is insufficient data available to confirm whether native pastures are able to sequester higher levels of SOC than sown pastures, (Robertson pers. comm. 2014). However, many native pastures inherently have higher SOC than sown, simply because they remain relatively undisturbed. Many improved pastures have still not regained the original SOC prior to clearing and disturbance (Eckard, pers. comm. 2014). Improved pastures generally have greater ability to sequester soil carbon than unimproved native pastures, (which usually have low P levels) due to their higher productivity (Chan et al. 2010).

3.6 Practice options and evidence for cropping systems

One of the projects funded under the Climate Change Research Program (CCRP) program was DEPI's '*Soil carbon in cropping and pasture systems of Victoria*'. Results from the field trials across eight regions representing the climatic range of the Victorian cropping industry, showed that management practices such as fertiliser application, cultivation, stubble retention, crop rotations and grazing management had relatively small or no effects on SOC stocks, (DAFF 2012). The authors also concluded that the potential for significant and verifiable soil C accumulation in Victoria's croplands is limited, and it would generally take 10–25 years for the soil carbon changes to become measurable using conventional soil sampling and analytical methods (Robertson and Nash 2012).

In Tasmania, SCaRP project no. 11 researchers concluded, the following hierarchy of influence of variables on SOC: Soil order > mean annual rainfall > land use > cropping frequency > tillage type. They also concluded that, aside from changing land use from cropping to pasture, increasing pasture phases and shifting to minimum and no-tillage cropping are likely to be key mechanisms farmers can use to increase soil carbon.

3.6.1 Reducing bare fallow phases in crop rotations/cover crops

Periods of fallow between crops leave soils exposed to wind and water erosion which can lead to soil carbon losses. Losses continue during fallow without any new carbon inputs from vegetation such as cover crops which help mitigate this. There is strong theoretical evidence, backed by cropping trial results that soil carbon losses are reduced through either the elimination, or at least reduction in the length of time, of bare fallow periods in the cropping cycle, (Robertson pers. comm. 2014; Cotching 2009).

3.6.2 Cropping - stubble retention, minimum tillage and direct drilling

Stubble retention can potentially reduce the extent of carbon losses by reducing the physical loss of top soil and hence, carbon, from erosion, and may reduce SOC stock losses. However, most trials indicate that retention of stubble, (as an alternative to stubble burning or other forms of removal), generally leads to little, if any, long term increase in SOC (Dalal et al. 2011; Robertson and Nash 2012; Sanderman et al. 2010).

Powlson et al. (2011) noted that most of the organic carbon added in straw will decompose and be returned to the atmosphere as CO_2, with only a fraction being retained in soil. Under temperate climate conditions, typically about one-third of plant material added to soil is retained after one year, with about two-thirds being emitted to the atmosphere (Powlson et al. 2011).

There are many situations where carbon increase, from stubble retention, has been measured in the top 5-10 cm of soils, but this is negated by a decrease in carbon at greater depth, (Sanderman et al. 2010; Robertson pers. comm. 2014). Surface residues decompose with only minor contribution to SOC pool and any increases in SOC from stubble retention and/or minimum tillage, tends to be small and emerge over the long-term (10+ years) (Robertson pers. comm. 2014). In general, increases in SOC from reduced tillage may also be much smaller than previously claimed, at least in temperate regions (Sanderman et al. 2010; Powlson et al. 2011). Minimum tillage and direct drilling, in comparison to multiple-pass conventional cultivation, has generally shown to result in little SOC benefit (Sanderman et al. 2010). Furthermore, although there are many situations where SOC increase has been measured in top 5-10 cm, this is usually negated by a decrease in deeper soil (Sanderman et al. 2010; Lam et al. 2013).

Some potential may exist to increase C sequestration in soil under no-till in higher rainfall areas (>550 mm in southern Australia and >700 mm in subtropical Queensland) (SCaRP no 8, CSIRO 2009a). Chan et al. (2003) reported that significantly higher soil C under conservation tillage only occurred in the wetter regions of Australia (>500 mm rainfall) where soil water was not limiting plant growth.

3.6.3 Inclusion of various pasture phase systems in rotation with crops

In mixed cropping/pasture systems, SOC levels generally decline under cropping phases and increase during the pasture phases, (CSIRO 2009; Chan et al., 2010). Maximizing pasture phases in mixed cropping systems, is likely to build up soil carbon levels, since pastures generally return more carbon to the soil than crops, (Sanderman et al. 2010; Chan et al., 2010). Under pastures, soils tend to have higher SOC levels than soils under crops because they have higher root to shoot ratio than many crops, which are relatively undisturbed and decompose at lower rates. This trend is usually even more so as rainfall increases (Chan et al., 2010).

SCaRP Project no 7, which investigated soil carbon levels in cropping and pasture systems of central and northern NSW, concluded that increasing the proportion of pasture may be a viable option for sequestering carbon in mixed farming systems.

In general, research into the inclusion of *leguminous pastures* in rotation with crops, as compared to continuous cropping with non-legumes, or pasture phases incorporating non-leguminous pastures, appear to be an effective way of increasing SOC in many situations, particularly where nitrogen levels are limiting soil fertility, (Robertson pers. comm. 2014). There may also be a reduction in total GHG emissions from replacement of added nitrogen fertiliser (savings from manufacture, transport and CO_2 release from urea hydrolysis) (CSIRO 2009a).

Inclusion of *non-leguminous pastures* in rotation with crops, compared to continuous cropping with non-legumes has shown to be an effective way of increasing soil carbon in *some* situations but has shown to be ineffective in others. In terms of GHG emissions reduction, inclusion of non-leguminous pasture phases in cropland may potentially increase the need for nitrogen fertiliser resulting in additional N_2O emissions and increased CH_4 emissions during the livestock production phase which would need to be accounted for if GHG emissions reduction is a driver for such land use change (Barlow et al., 2011; Cowie 2010a).

Research suggests that there is some evidence that inclusion of *leguminous crops* (pulses) in rotation with non-leguminous crops (cereals & oilseeds) can lead to an increase in SOC (in comparison to continuous cropping with non-legumes), especially where nitrogen levels are limiting soil fertility. However, most studies show no effect (Robertson pers. comm. 2014). SOC effects seem likely to be influenced more by how the crop was established rather that by the crop itself (Eckard pers. comm. 2014).

3.6.4 Increasing productivity through increasing irrigation

There is little evidence that increasing productivity through increasing irrigation will effectively increase SOC as crop yield and production efficiency increases do not necessarily translate to increased carbon returned to soils. Furthermore, there is the potential trade-off between any increase in carbon returned to soil through increased vegetative growth and increased decomposition rates (Sanderman et al. 2010).

3.6.5 Increasing productivity through fertiliser application

There is good research evidence that increasing productivity through fertiliser application can increase SOC, but not in others. Positive results are mostly likely to occur where soil nutrient levels are deficient, (in comparison to using no fertiliser or other nutrient applications). Evidence has been shown for nitrogen and phosphorous application and is likely to hold for other nutrients too (Robertson, pers. comm. 2014).

Adding more nitrogen fertiliser leads to increased plant growth, hence increased root growth leading to more SOC. However, as with increased irrigation, there is a potential trade-off between increased carbon returned to soil and increased decomposition rates (Sanderman et al. 2010). High nitrogen inputs could lead to more N_2O emissions (Dalal et al. 2003; Chan et al. 2008). Also evidence that applying fertiliser, in excess of plant requirements, will have no effect or even a negative effect on soil carbon and potentially increase N_2O emissions (Eckard pers. comm. 2014).

3.7 Practice options and evidence for mixed systems or system conversion

3.7.1 Conversion of cropping to permanent pasture

There is very strong evidence that conversion of cropping to permanent pasture will increase SOC in most situations. Pastures generally return more C to soils than crops (Sanderman et al. 2010; Cotching 2009; Chan et al. 2010). Current research suggests that where there is low SOC, with high potential, then the net effect of the conversion on GHG emissions may be positive initially, but after about 20 years it would switch the other way (Eckard pers. comm. 2014). The beneficial effect on SOC is greater where cropping has been long-term (Robertson pers. comm. 2014).

Powlson et al. (2011) conclude that arable soils usually have a much smaller SOC content than the equivalent soil under forest or grass, and that land use conversion from cropping to permanent pasture will almost always lead to an accumulation of SOC. They provide examples of considerable SOC accumulation after land-use change, from arable to woodland, at two temperate region sites in the UK.

Conversion of cropping land to permanent pasture is widely considered to lead to an increase in soil carbon stocks (Luo et al. 2010). However, conversion to pasture for food production in Australia almost exclusively involves ruminant livestock (sheep, cattle, goats) resulting in significant CH_4 and N_2O emissions, (Lam et al. 2013; Sanderman et al. 2010). Under the Australian GHG accounting system, the majority, (about 87 per cent) of the total GHG's in the farm livestock category of Australia's National Greenhouse Gas Inventory is enteric CH_4 from ruminants. As CH_4 and N_2O emissions are losses of energy and nitrogen (respectively) from livestock production, reducing emissions has potential to deliver productivity benefits to farmers. While some mitigation methods could be considered best practice in terms of livestock production, broad-scale extension to create awareness of the research and assist livestock producers in capturing benefits while reducing emissions has only recently begun.

Lam et al. (2013) reported that, in Australia, the use of pasture generally outperformed the other agricultural practices that they considered in terms of sustainability for at least 40 years. However, in relation to the issue of potential increasing CH_4 emissions, they noted two other problems that could arise from increased pasture in Australia, (in particular permanent pastures):

- increased demand for irrigation water to maintain pastures (to be effective in storing more soil carbon), and
- less efficient use of solar radiation/ha to produce animal products compared to food crops.

Researchers in Australia and overseas are developing a range of livestock emissions mitigation methods. Methods include the use of dietary tannins and oils, improved genetics, animal husbandry and reproductive performance, and improving animal feed quality, among others.

Another issue relating to conversion of cropping to pasture, is the risk of 'leakage' which is usually used in reference to emissions being transferred from one country to another, (Lee et al. 2007). However, it can also work from one farm to another, and refers to the risk of GHG mitigation actions leading to increasing carbon losses elsewhere. For example, if a cropping farmer changes to pasture to increase SOC, apart from the implied increase in CH_4 and N_2O emissions, the market for the previous crop won't necessarily have diminished, so pasture or forest somewhere else will need to be cleared to grow that crop. Shifting to pasture may not be a good strategy for GHG emissions reduction if it produces less food for more emissions, (James pers. comm. 2014).

3.7.2 Shifting from annual to perennial pasture systems

Perennial pasture plants can utilise water throughout the year which is likely to lead to an increased below ground allocation of biomass and hence carbon (Sanderman et al. 2010). For example perennial pastures, such as phalaris have long-lived deep root systems which can utilise water at depth. Furthermore, annual pastures die off returning their above and below ground biomass to soils every year whereas the carbon stored in perennial pasture root systems is less readily decomposed than carbon in soils close to the surface (Chan et al. 2010).

Current research suggests that where there is low SOC, with high potential, then the net effect of converting to perennial pastures may be positive initially, but after about 20 years it would switch the other way (Eckard pers. comm. 2014). Overall, however, there is currently little data available and the evidence is equivocal as to the potential SOC sequestration benefit of shifting from annual to perennial pastures (Chan et al. 2010; Robertson pers. comm. 2014).

A new Carbon Farming Initiative (CFI) methodology has recently been approved by the federal government; *'Sequestering carbon in soils in grazing systems'* which applies to land managed using a range of activities to build soil carbon including, but not limited to:

- Converting cropland to permanent pasture
- Rejuvenating pastures, or
- Changing grazing patterns.

3.7.3 Shifting from conventional to organic farming

There is strong anecdotal evidence that alternative farming systems such as biodynamic and organic systems can capture and store more SOC than their traditional counterparts. However, such evidence is inconclusive due to a lack of available data (Sanderman et al. 2010; Robertson pers. comm. 2014). Furthermore, a negative impact from manure or compost-based systems can be an increase in N_2O emissions, (Powlson et al. 2011). Results of studies give variable outcomes depending on the specifics of the organic system i.e. manuring, cover crops etc. (Sanderman et al. 2010).

3.7.4 Increasing productivity through irrigation

There is good evidence in some situations but not in others, that increasing productivity through irrigation will lead to increased SOC levels (Robertson, pers. comm. 2014). Increased crop yields and production efficiencies won’t necessarily lead to increased carbon returned to soils; there is the potential trade-off between increased carbon returned to soils and increased decomposition rates (Sanderman et al., 2010).

3.7.5 Enhanced crop productivity and managing nitrogen inputs

The IPCC (2007) estimate that 70% of the total GHG emissions from agriculture are associated with nitrogen-based fertilisers; a combination of CO_2 and nitrous oxide (N_2O) from its manufacture and N_2O emissions, direct and indirect, from its use.

MacEwan (2007) noted that there are limited prospects for soil carbon sequestration to have a net long term positive impact on climate change mitigation and that a better solution resides in mitigating climate through management of nitrous oxide (N_2O). Over-emphasising the benefits of soil C sequestration may diminish other measures that are at least as, if not more, effective in reducing GHG emissions such as slowing deforestation and increasing efficiency of N use in order to decrease N_2O emissions (Powlson et al. 2011). Better management of N inputs in agricultural production can have a number of other benefits for the environment and farm profitability. Less N input can reduce nitrate leaching and runoff, (both of which can be associated with contamination of groundwater and streams) and can improve farm profitability through improved efficiency of fertiliser inputs (Cotching 2009).

Barlow et al. (2011 p.2) recommended ‘‘Further research into the potential perverse impacts of management strategies aimed at increasing soil carbon due to the intimate linkages between soil carbon and nitrogen cycles’’. They noted that CFI approved practices that increase soil carbon could significantly increase nitrogen-based GHG emissions in some regions of Australia.

The fertiliser industry has developed and commercialised a range of enhanced-efficiency fertilisers for use in Australia. These are typically either coated, slow-release fertilisers or contain chemicals designed to inhibit processes which lead to gaseous losses. Farmer adoption of these fertilisers has generally been slow in Australia to date. Efforts to understand and mitigate N_2O production in farming systems is a significant area of research within DEPI and DAFF at present. For example, a new Fertcare Carbon Farming Extension Project, led by Fertilizer Australia, aims, amongst other things, to provide agronomists with decision support tools to help them guide farmers on land based GHG emissions and soil carbon relevant to their farm nutrient management plans.

3.7.6 Increasing productivity through fertilisation

There is good evidence in some situations but not in others, that increasing productivity through increasing fertilizer input will lead to increased SOC levels (Robertson, pers. comm. 2014). As for irrigation, there is the potential trade-off between increased carbon returned to soils and increased decomposition rates, (Robertson, pers. comm. 2014). Increasing nitrogen use needs to be balanced against GHG emissions associated with manufacture and use of fertilizer (IPCC 2014a; Powlson et al. 2011; Barlow 2011; Cowie 2010).

A CFI methodology is being developed for increasing productivity through fertiliser application, though it will initially only be for cotton (Eckard pers. comm. 2014).

3.7.7 Top soil addition of organic matter e.g. compost, manure

There is considerable evidence, both theoretical and evidentiary, in many situations that SOC can be increased through the addition of a wide variety of organic materials (Sanderman et al. 2010). The extent to which adding organic matter benefits SOC depends on the type, composition and amount of organic material applied. Carbon derived from organic inputs that are high in lignin, may reside in soil longer than the labile carbon in crop residue.

Direct input of carbon often in a more stable form, into soil may also have the benefit of stimulating plant productivity. Manure, composts or some other organic residues may have the added benefit of recycling nutrients. Materials, with a wide C-to-N ratio such as cereal straw or paper waste, tend to immobilize inorganic N which may be beneficial in situations where there is excess N and nitrate leaching is a serious risk (Powlson et al. 2011).

However, in regards to genuinely reducing carbon sequestration, ie, resulting in GHG emissions reduction, Powlson et al. (2011 pp1.) concluded that ''Adding organic materials such as crop residues or animal manure to soil, whilst increasing SOC, generally does not constitute an additional transfer of C from the atmosphere to land, depending on the alternative fate of the residue''. For example, addition of straw to soil usually leads to an increase in SOC content, even though this may be slow and not measurable for some years. If the alternative fate of the straw is in-field burning, then addition to soil genuinely represents additional retention of carbon in soil.

Stubble burning is still a common practice in some parts of Australia, such as the western districts cropping land of Victoria. Hence conversion to a non- burning regime may result in genuine carbon sequestration on such sites. Similarly, for manures and biosolids, if the alternative is disposal to a landfill (that doesn't capture, flare or use captured methane), then application to land may represent an 'avoided emission' of methane in addition to a degree of soil carbon sequestration.

Results from SCaRP project no. 7 investigated the soil carbon levels in cropping and pasture systems of central and northern NSW. On the northern tablelands, their research indicated no detectable difference between cropped sites treated with organic amendments and those receiving chemical fertiliser in regard to their impact on soil carbon stocks.

3.7.8 Cropping – Subsoil manuring

Generally, subsoils contain smaller concentrations of carbon than the adjacent topsoil, with the implication that subsoils may contain unused capacity for carbon storage. If this capacity could be used it could, in principle, increase the potential for genuine additional carbon sequestration in soils. In addition, there are some indications that organic carbon in subsoil is more strongly stabilized than carbon in topsoil (Powlson et al. (2011).

Sub-soil manuring is a practice where large volumes of nutrient rich organic matter (10-20 tonne/ha) are deposited into the upper layers of clay subsoils. Sub-soil manuring has the potential to increase soil carbon at depth by encouraging deeper root development through incorporation of high rates of organic matter (Peries pers. comm. 2014). Recent Victorian DEPI trials have indicated an increase in crop yield of 40% to 95% across sites and seasons. These results, to date, have lasted at least 5 years and are yielding good returns on investment. Regarding profitability, preliminary Victorian results show that at the 20t/ha rate, investment return exceeded $500/ha at Penshurst and $400/ha at Derrinallum each year for four years, representing an annuity in addition to the standard eight per cent per year investment return that would be expected from such an investment of capital (GRDC 2013). Sub-manuring trails are expected to commence near Launceston early in 2015 (Peries pers. comm. 2014).

A DAFF funded project 'Evaluating soil carbon sequestration from sub-soil amelioration trials -

Southern Farming Systems' is trialling and demonstrating the sub-surface placement of manures at various depths to increase soil carbon sequestration and enhance crop productivity in southern Australia. The project is due to be completed mid-2015.

SCaRP project no 13 examined SOC in Western Australian soils and concluded that maximum storage of SOC in WA soils is rarely achieved, due to sub-optimal climatic conditions. Although the WA modelling suggests that the 0-0.1 m layer is largely saturated in terms of carbon storage, the researchers also found that soils below 0.1 m are currently below half their potential storage capacity. They concluded that where cost effective to do so, it is important that management practices remove any constraints to plant growth and that practices that deliver organic matter below the surface 0.1 m soil layer are more likely to build SOC.

3.7.9 Biochar

Biochar is a more stable form of charcoal produced from heating natural organic materials under high temperature and low oxygen in a process known as pyrolysis. Biochar can enrich soils, potentially acting as a stable carbon sink for anywhere between 100-1,500 years (CSIRO 2013a). Interest is growing in the potential use of biochar to build soil carbon stocks. A summary of biochar's role in soil and climate change and research needs was undertaken by CSIRO (2009). It is generally accepted that biochar is a highly stable form of carbon and as such has the potential to form an effective C sink, therefore sequestering atmospheric CO_2.

The potential GHG reduction benefits of biochar, as identified by CSIRO (2009, 2013) include:

- Stabilisation of biomass C i.e. delayed decomposition
- Stabilisation of native soil carbon
- Reduced emissions from N fertiliser manufacture by increasing or retaining plant productivity with a lower amount of fertiliser use and more efficient retention of nutrients and avoided leaching from the soil profile.
- Reduced nitrous oxide emissions from soil
- Increased plant growth leading to increasing C sequestration by plants
- Reduced fuel use in cultivation and irrigation
- Avoided emissions from waste management from urban, agricultural and forestry
- Avoided fossil fuel emissions due to use of syngas as renewable energy
- Displacing fossil fuel use through bioenergy production
- Enabling soil and vegetation to adapt to climate change by increasing water holding capacity of soils, soil pliability and increasing water infiltration.

Biochar effectively removes C from the carbon-cycle due by locking C up for long periods. If bioenergy is produced and utilised as of part the biochar production system, biochar can be a very effective product for storing carbon in the long term, though this would need to be validated through a full life cycle analyses (CSIRO 2013). Biochars produced at higher temperature are more stable than those pyrolysed at low temperature. The CSIRO State that "biochar is chemically and biologically in a more stable form than the original carbon form it comes from, making it more difficult to break down. This means that in some cases it can remain stable in soil for hundreds to thousands of years", CSIRO, (2013a pp.1). However, Cowie pers. comm (2010) suggested that there are few studies quantifying the net GHG impacts of actual biochar systems. To calculate the mitigation benefits of biochar, a life-cycle approach needs to be undertaken, taking into consideration all aspects of the biochar system, including - the type of biomass, it's procurement, the type of production system and technology, (pyrolyser) used, and its application. To determine any carbon sequestration benefits, each stage needs to be assessed as to the net GHG impacts across the entire system (CSIRO, 2009). For example, producing biochar in a poorly designed pyrolyser can lead to the production of toxic and/or powerful greenhouse gases, such as methane which may negate biochar's carbon sequestration benefits.

A Life Cycle Analysis of biochar produced from three different feedstocks concluded ''Biochar may at present only deliver climate change mitigation benefits and be financially viable as a distributed system using waste biomass'' (Roberts et al. 2010 pp 1.).

In a recent review of biochar research, the authors state that:

‘‘there are not enough data to draw conclusions about how biochar production and application affect whole-system GHG budgets. Wide-ranging estimates of a key variable, biochar stability in situ, likely result from diverse environmental conditions, feedstocks, and study designs. There are even fewer data about the extent to which biochar stimulates decomposition of soil organic matter or affects non-CO2 GHG emissions. Identifying conditions where biochar amendments yield favourable GHG budgets requires a systematic field research program. Finally, evaluating biochar's suitability as a climate mitigation strategy requires comparing its effects with alternative uses of biomass and considering GHG budgets over both long and short time scales’’ (Gurwick et al. 2013 pp 1).

A DPI (2009) study into the feasibility of biochar production in Victoria suggested that for a 100,000-tonne facility to be profitable, the delivered cost of the feedstock needs to be below about $40/t (delivered) or failing a low feedstock price, profitability requires a biochar price over $300/t. The biochar producer would be a price-taker for the electricity produced and Renewable Energy Certificates created. Note: These conclusions need to be considered in the context of the many assumptions made by the researchers.

Internationally, several countries have endorsed the use of biochar as a climate mitigation and C sequestration tool through a submission to United Nations Framework Convention on Climate Change (CSIRO 2009). The International Biochar Initiative, (IBI) has prepared internationally accepted standards for biochar characterisation and the development of standards pertaining to biochar production and utilisation, (see the IBI website for details).

Berndes et al. (2010) compare biochar production systems with the aim of developing metrics that can distinguish which of the various biomass production land-use systems have the highest GHG mitigation benefit with reference to soil amendment and energy production.

A recent NSW DPI trial indicated that some of the biochars tested were effective in reducing emissions of N_2O from soil and that overall the reduction in N_2O emissions was significant due to the multiplying factor used for N_2O of 350, (ANZBRN undated). Application of biochar to soils “can potentially reduce N_2O emissions when soil conditions favour conversion of nitrate to nitrous oxide” (DAFF 2013 pp 31). In Australia, NSW DPI, in conjunction with CSIRO, is leading the research into biochar and currently claims to be running the world's largest demonstration of biochar, with over 150 field plots under management. The NSW DPI website outlines a number of studies that they are undertaking to help quantify any possible carbon sequestration benefits of biochar.

Sources of biochar information include the CSIRO, DPI NSW, the International Biochar Initiative, (IBI) and the Australia New Zealand Australian Biochar Researchers Network (ANZBRN). The $1.4 million National Biochar Initiative has been a component of the federal government Climate Change Research Program. An outline of the key findings from biochar research undertaken through this Program as well as related projects being funded through the Biochar Building Capacity and Round 1 of Filling the Research Gap’ can be found at the Biochar Capacity Building Program website.

3.8 Summary of terrestrial sequestration options

Terrestrial carbon sequestration options and their potential impact on soil carbon stocks and greenhouse gas emissions reduction are summarised in Appendix A.

3.9 Other relevant terrestrial carbon sequestration research in Australia

The federal Department of Agriculture have funded numerous Action on the Ground and Filling the Research Gap (FRG) projects, which are either underway or recently completed, and are relevant to the south eastern Australia region. The FRG program includes the National Soil Carbon Program which is undertaking research in to the sequestration and measurement of organic carbon in soil across Australia, many of which are relevant to south eastern Australia.

A number of these projects are on-going, directly trialling sequestration activities including various types and configurations of environmental plantings, perennial native grasses, as well as compost and biochar amendments for increased carbon sequestration. A summary of the key projects can be found at the DAFF website.

Another recently completed DEPI-led project funded through FRG has a research paper due to be published in 2014 titled: 'Increasing soil carbon in eastern Australian farming systems: Linking management, nitrogen and productivity', (Fiona Robertson, DEPI, pers. comm., Feb 2014). The research assessed practices that previous research or farmer experience suggest may have the potential to sequester carbon, including pastures in crop rotations, alternative residue management and alternative grazing systems.

Building on previous research, a component of the FRG, (the Soil Carbon Research Program), includes a number of projects relevant to south eastern Australia , including 'Environmental plantings for soil carbon sequestration on farms' (Paul pers. comm. 2014). This national project is supporting the extension of the Carbon Farming Initiative (CFI) methodology for mixed-species environmental plantings to include carbon in soil. Work on carbon sequestration under environmental plantings is also being extended by two other related, CSIRO-led sequestration projects:

(i) Soil carbon under environmental plantings is due to be completed around March 2015, (Paul, pers comm.). The project aims to improve capacity to estimate how management affects soil carbon on agricultural–environmental planting sites that have low opportunity costs. This project will also help provide information to land managers interested in participating in CFI reforestation on marginal farm lands by enhancing commonly used carbon accounting tools to account for both the above and below ground potential of environmental plantings across a range of site and management conditions.

(ii) Carbon estimation tool development; change in biomass carbon in complex woody systems. The objective of this project is to develop a new hybrid carbon accounting method that combines elements of measurement-based approaches with the more cost-effective FullCAM modeling approach, also providing a CFI Methodology using this accounting approach. DEPI, Victoria, is a key partner.

4. Aquatic (blue) carbon sequestration

4.1 What is blue carbon?

Vegetated aquatic coastal ecosystems, in particular tidal wetlands, mangroves and seagrass beds are important carbon sinks because they:

- are naturally highly productive ecosystems,
- efficiently trap sediments and hence, carbon, through continual tidal movement,
- sequester atmospheric carbon.

In combination these ecosystems build-up stocks of carbon in submerged sediments and organic-rich soils. These coastal carbon stocks stored in the biomass and deep sediments in these aquatic ecosystems are often referred to as ‘blue carbon’ (McLeod et al. 2011).

The United Nations Environment Program estimate that fifty-five per cent of the atmospheric carbon captured by living organisms is taken up at sea and that 50-71% of this is captured by the ocean’s vegetated ‘Blue Carbon’ habitats which only cover less than 0.5% of the seabed (UNEP’s Blue Carbon Initiative fact sheet, Nellerman et al. 2009). Although blue carbon habitats comprise only 0.05% of the plant biomass on land, they store a comparable amount of carbon per year, ranking them amongst the most intense carbon sinks on the planet (Nellerman et al. 2009).

Blue carbon is captured and stored up to 100 times faster than in forests and stored for thousands of years, (CSIRO 2014). However, blue carbon is rapidly released back to the atmosphere as CO_2 and methane via conversion of ecosystems such as tidal marshes, mangroves to terrestrial land uses, or destruction of seagrass beds (Donato 2012). New evidence indicates that land-use conversion of vegetated aquatic ecosystems is a very significant source of GHG’s (European Commission 2012).

Restoring coastal wetlands has the potential to stop drainage and degradation-induced releases of CO_2 and CH_4 and reactivate carbon sequestration. Hence, for the above reasons, carbon stored via protection and restoration of coastal aquatic ecosystems can make better economic sense than the alternative of terrestrial carbon storage. Healthier coastal ecosystems will also enhance industries such as fisheries and tourism, improve water quality and aid flood and storm surge mitigation (Nellerman et al. 2009).

Given the potentially large carbon emissions from degraded coastal ecosystems and other wetlands, blue carbon may offer a new opportunity for carbon sequestration, especially if incentives become available to encourage their maintenance, enhancement and/or restoration, and/or other ecosystem benefits are factored in.

4.2 What are the global and Australian stocks of blue carbon?

The actual amount of carbon stored by these coastal ecosystems is an area of active research, however the known and potential GHG emissions from their loss is becoming clearer (Pendelton et al. 2012). Estimates of annual carbon released from coastal ecosystems globally due to land-use change are between 0.15 and 1.02 Pg (billion tons) of CO_2, with a central estimate of 0.45 Pg CO_2, equivalent to around 3–19% of emissions from deforestation globally (Pendelton et al. 2012).

Estimates of cumulative loss over the last 50–100 years range from 25–50% of total global area of each of the three types; tidal marshes, mangroves, and seagrass beds with an estimated continuing decline of ~0.5–3% annually depending on ecosystem type, amounting to ~8000 km^2 lost each year (Pendelton et al. 2012).

Current estimates of coastal carbon stocks around Australia are limited along with a poor understanding of the processes responsible for sequestering the carbon. The CSIRO’s Coastal Carbon Cluster (CCC) formed in 2013, aims to quantify for the first time how Australia's marine environment stores atmospheric CO_2. Research includes collation of existing coastal carbon data for Australia and providing new data to enhance CSIRO’s modelling capacity to predict national coastal carbon budgets, (CSIRO 2014). A number of working groups are investigating various aspects of blue carbon under the CCC, including a recently compiled data-set to help derive mean rates of carbon stores for tidal marsh, mangrove and seagrass ecosystems, and to explore the variability among different ecosystems types and habitats.

4.3 Policy mechanisms for sequestration of blue carbon

In Australia, there is currently no policy mechanism for developing or maintaining blue carbon stocks and most of these reserves are managed by state and local governments. There is currently no approved CFI methodology for blue carbon, however, the University of QLD has a draft methodology '*Carbon sequestration through afforestation and/or reforestation of degraded mangrove habitats using the CFI reforestation modelling tool and sampling techniques for soil organic carbon*' which involves the afforestation and/or reforestation of degraded mangrove habitat through assisted natural regeneration, seeding or tree planting.

In October 2013, the IPCC adopted the 2013 Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands (Wetlands Supplement). It provides methods for estimating anthropogenic emissions and removals of greenhouse gases from inland peat lands and other wetlands on mineral soils, coastal wetlands including mangrove forests, tidal marshes and seagrass meadows, and constructed wetlands for wastewater treatment.

The U.S. Verified Carbon Standard, (undated) (VCS) recognised Wetland Restoration and Conservation as an eligible project activity for carbon finance in 2012. The VCS currently has a draft methodology that outlines procedures to quantify net GHG emission reductions and removals resulting from project activities implemented to restore tidal wetlands. Such activities include creating and/or managing the conditions required for healthy, sustainable wetland ecosystems.

In 2013, the American Carbon Registry (ACR) approved the first blue carbon methodology allowing landowners to earn carbon offsets from deltaic wetland restoration projects in the voluntary carbon market (ACR undated).

While blue carbon offers both sequestration and coastal adaptation benefits, it will also be important to consider the implications of future sea level rise for blue carbon sinks and their management over the longer term.

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Appendix A

Tables 1, 2, 3 and 4: A summary of practice options and evidence for various land management practices to sequester carbon

Table 1: Practice options and evidence for cropping systems

Practice option	Research evidence	Relevant CFI methodology	Benefits for carbon sequestration	Negative impacts / risk
Elimination or reduction of the length of time of bare fallow phases in crop rotations by using cover crops.	Very strong evidence for reducing carbon loss, near universal finding.[A]	None approved	Losses continue during fallow without any new C inputs – cover crops mitigate this. Added potential to reduce C losses through reduced erosion.[C, 16, 17]	None documented
Stubble retention (cf. stubble burning /removal)	Most studies show no effect though good evidence in a few situations.[A]	None approved	Greater C return to the soil is likely to reduce extent of C losses and may increase SOC stocks.[C, 18]	Any increases are small and emerge over long-term (10+ years).[A,3.] Many situations where C increase measured in top 5-10 cm, but this is negated by a decrease in C at greater depth.[A]
Minimum tillage and direct drilling (cf. multiple-pass conventional cultivation)	Most studies show no effect though some good evidence in a few situations.[A]	None approved	Direct drilling reduces erosion and destruction of soil structure thus slowing decomposition rates.[C]	Reduced tillage has shown little SOC benefit[3. C]. Any increases are small and emerge over long-term (10+ years).[A] Surface residues decompose with only minor contribution to SOC pool.[3, C] Many situations where C increase measured in top 5-10 cm, but this is negated by a decrease in deeper soil.[A]
Inclusion of leguminous pastures in rotation with crops (cf. continuous cropping with non-legumes).	Strong evidence in many situations, but not in others.[A]	None approved	Particularly effective where N is limiting.[A] Pastures generally return more C to the soil than crop.[C]	Potential of increased CH_4 and N_2O from livestock production systems need to be accounted for from conversion of cropping to grazing land.[5, 6]
Inclusion of non-leguminous pastures in rotation with crops (cf. continuous cropping with non-legumes).	Evidence in some situations but not in others.[A]	None approved	Depends on dry matter inputs from the pasture.[A] Pastures generally return more C to the soil than crops.[C]	Potential of increased CH_4 and N_2O from livestock production systems need to be accounted for from conversion of cropping to grazing land.[5, 6] Lack of legumes likely to increase need for N fertiliser resulting in

				additional N_2O emissions.
Inclusion of leguminous crops (pulses) in rotation with non-leguminous crops (cereals & oilseeds) (cf. continuous cropping with non-legumes).	Good evidence but only in very few situations	None approved	Potentially effective where N is deficient.[A]	Most studies show no effect.[A] SOC effects likely to be influenced more by how the crop was established rather that the crop itself.[B]
Increasing productivity through increasing irrigation	Yield and efficiency increases do not necessarily translate to increased C return to soil.[C]	None approved		Potential trade-off between increased C return to soil and increased decomposition rates.[C]
Increasing productivity through fertiliser application (cf. zero fertiliser or other nutrient applications)	Good evidence in some situations but not in others.[A]	CFI methodology being developed. However, initially focused just on cotton.[B]	Good evidence where soil nutrient levels are deficient. Evidence re: N and P, but likely to hold for other nutrients too.[A]	Potential trade-off between increased C return to soil and increased decomposition rates.[C] Adding more N fertiliser leads to increased plant growth, hence increased root growth leading to more SOC. However, high N inputs would lead to more N_2O emissions.[B] Evidence that applying fertiliser in excess of plant requirements has no effect or negative effect on soil C.[A]

Table 2: Practice options and evidence for mixed systems or system conversion

Practice option	Research evidence	Relevant CFI methodology	Benefits for carbon sequestration	Negative impacts / risks
Top soil application of imported organic material (compost, manure etc)	Strong evidence in many situations for wide variety of organic materials.[A] High confidence in improving C sequestration rates based on both theoretical and evidentiary lines.[C]	Currently, no CFI methodology approved	Depends on amount and type of material applied.[A] Direct input of C, often in a more stable form, into soil may stimulate plant productivity.[C]	The increased soil C may not constitute genuine C sequestration (only C transfer), depending upon the alternative fate of the organic material.[3]
Sub-soil manuring	Current DAFF funded project is investigating carbon sequestration through sub-soil manuring.[13]	None approved	Likely that the practice has the potential to increase soil carbon at depth.[15]	The increased soil C may not constitute C sequestration (only C transfer), depending upon the alternative fate of the organic material.[3]
Conversion of cropping to permanent pasture	Very strong evidence in most situations.[A]	New CFI methodology: Website here Sequestering carbon in soils in grazing systems; applies to land that is either under permanent pasture, or that is converting to permanent pasture.	Pastures generally return more C to soils than crops.[C,16] Current research suggests that where there is low SOC, with high potential, then the net effect of the conversion on GHG emissions may be positive initially, but after about 20 years it would switch the other way.[B, 14] Effect is greater where cropping was long-term.[A]	The added CH_4 and N_2O from ruminants may more than neutralise the increased soil carbon benefit.[B, 5] Benefit will likely depend greatly upon the specifics of the switch.[C] Shifting from cropping to pasture, without any decrease in market demand for crops, will lead to other land being put into cropping, merely transferring SOC losses to another farm.
Shift from annual to perennial pasture species.	Evidence equivocal, little data available.	A new Carbon Farming Initiative (CFI) methodology has recently been approved by the federal government; 'Sequestering carbon in soils in grazing systems' which applies to land managed using a range of	Plants can utilise water throughout the year, increased below ground allocation but few studies to date.[C] Current research suggests that where there is low SOC, with high potential, then the net effect may be positive	

		activities to build soil carbon including, but not limited to: - converting cropland to permanent pasture - rejuvenating pastures, or - changing grazing patterns.	initially, but after about 20 years it would switch the other way.[B]	
Conventional to organic farming system	Insufficient data available.[A]	Currently, no CFI methodology approved		Variable outcomes depending on the specifics of the organic system (i.e. manuring, cover crops etc)[C]
Stabilised C in Biochar which is then added to soil for potential long term C sequestration benefits and productivity gains.	Work being undertaken via the National Biochar Intitative..	Biochar is on the CFI Positive list of activities, however there are no current approved methodologies though 2 biochar methodologies for a single feedstock are currently being developed [Web]()	C in plant material, converted to a highly stable form of C as biochar, can be regarded as genuine C sequestration. Biochar may also reduce N_2O and CH_4 losses.[1,2,3, 5]	Validation of GHG mitigation benefits of biochar, requires a full life-cycle assessment across the whole system – i.e. biomass source and procurement, biochar production system, and its application.[1,2,3, 5] Evidence for reduced N_2O is mainly because the biochar changes the soil C:N ratio and thus immobilises soil N. However, more N may need to be added to the system to become productive again.[B] Point of 'sequestration' is at the biochar pyrolyser. Land application is technically carbon transfer and not actual sequestration.[B]

Table 3: Practice options and evidence for grazing systems

Practice option	Research evidence	Relevant CFI methodology	Benefits for carbon sequestration	Negative impacts / risks
Grazing management	Strong evidence that over-grazing reduces soil C eg. via erosion losses.[A] Evidence for other grazing practices (stocking intensity, duration, rotational /set stocking etc.) is equivocal or non-existent.[A, 10]		Strong evidence that over-grazing reduces soil C eg. via erosion losses.[A]	Long term trials at Hamilton, (Vic) show no change in SOC for two plus decades under a range of grazing management systems.[B] Any soil C change as a result of change in grazing pressure takes many years to be detectable.[10]
Increasing productivity through irrigation	Good evidence in some situations but not in others.[A]			Potential trade-off between increased C return to soil and increased decomposition rates.[C]
Increasing productivity through fertilization	Good evidence in some situations but not in others.[A]			Potential trade-off between increased C return to soil and increased decomposition rates.[C] Likely to depend on original nutrient status.[A] Increasing N use needs to be balanced against GHG emissions associated with manufacture and use of fertilizer.[2,3,4,5]
Native v. sown pastures	Insufficient data available.[A]			Many native pastures have higher SOC than sown, simply because they remain relatively undisturbed. Many improved pastures have still not regained the original SOC prior to clearing and disturbance.[B]

Table 4: Practice options and evidence for forest systems

Practice option	Research evidence	Relevant CFI methodology	Benefits for carbon sequestration	Negative impacts / risks
Protection of native forest	Currently only debris and biomass covered in C sequestration methodology	One CFI methodology - Link to website here Applies to protection of native forest, which has received government consent to be cleared and converted to	Annual production, minus natural loss, is now returned to soil: active management to replant native species often results in large C gains.[C, 2, 3]	Unlikely to be a significant activity for carbon sequestration in Victoria under current native vegetation controls.

		cropland or grassland.		
Reforestation/Afforestation with any (non-weed) tree species. **Excludes industrial , (harvested) plantations, (see section below)**	Currently only debris and iomass covered in C sequestration methodology NOTE: Work underway to include soil C changes through this types of revegetation through CFI methodology. Hence, all pools will be covered - not just debris and biomass.[D]	Three current CFI Methodologies. Link to website here Applies to any (non-weed) tree species.	Converting agricultural land to woody vegetation generally optimises sequestration and environmental benefits where forests grown successfully on degraded land or land of limited agricultural value and/or where a carbon-only focus is avoided.[2,7,8,9.] May also provide a range of other economic and environmental benefits, including firewood (derived from coarse woody debris), shelter and/or to decrease soil erosion, waterlogging or salinity.[2,3,5,7,8,12,13] Carbon forestry appeared to be the best option for maximizing C sequestration in QLD study.[10]	A carbon price of at between $18[12] - $40t CO_2/year likely to be needed for carbon farming to be profitable in Australia under most plausible scenarios.[7, 8, 9.] Lower price (~$18/t) is relevant to 3-4 row farm forestry belts established on areas of lowest productivity on farms in higher rainfall areas.[12] Few areas economically viable for carbon farming only focussed schemes. Need to consider co-benefits of revegetation such as enhanced biodiversity, connectivity, erosion control etc in any incentive scheme design.[7, 8,9,10.] Supplementary payments may be needed to make biodiverse environmental plantings competitive with other land uses.[7, 8] Can potentially lead to monoculture plantations replacing biodiverse remnants, and unintended off-site impacts such as reduced water security. May have negative Indirect Land Use Change impacts if conversion leads to reduced agricultural production in one region being offset by increased conversion of land elsewhere, (though unlikely to be an issue in Victoria).

Environmental plantings/ Regeneration CFI Methodology applies only to local native species.	Currently only debris and biomass covered under these methodologies. NOTE: Work underway to include soil C changes in the environmental planting CFI methodology, hence, all pools will be covered - not just debris and biomass. [D,14]	Three current CFI Methodologies apply to local native species. Website link here 1. Environmental (plantings or seeding). 2. Human-induced regeneration of a permanent even-aged native forest, (2 methodologies) Also, draft CFI Methodology (DOIC endorsed): Quantifying carbon sequestration by permanent native mixed species, environmental or mallee plantings using Full CAM. [14]	See above. Cf. to harvested forests and plantations, more areas in the landscape available to carbon plantings as no need to locate them near processing facilities (potentially reducing negative adverse impacts of large plantings on water security. [13] Potentially low input cost using human – induced natural regeneration.	See above
Environmental plantings/ Regeneration of mallee eucalypt species on established on land receiving less than 600 mm annual rainfall	Currently only debris and biomass covered under these methodologies. NOTE: Work underway to include soil C changes in mallee plantings into this CFI methodology. [14]	One current CFI Methodology Website link here Applies to mallee eucalypt species established on land receiving less than 600 mm annual rainfall	See above. Young mallee and environmental plantings may sequester carbon at much greater rates than previously estimated. Highest sequestration rates generally found in narrow, dense belts with high stand densities and a high proportion of trees relative to shrubs. [12]	See above Can potentially lead to unintended off-site impacts such as reduced water security.
Native forest from managed growth	Harvesting, other than some permitted thinning excluded, under CFI	One current CFI Methodology Website here Based on above and below ground carbon using FullCAM	Should lead to an increase in SOC over time. [D]	
Forest management - Biomass production for bioenergy.		No current CFI Methodology -	Forests harvested periodically for bioenergy production sequester carbon, (both above and	Harvesting for bioenergy should lead to a decrease in SOC, (relative to longer

			below ground), at lower levels than unharvested forests in the short term. However, the total GHG mitigation effect of bioenergy plantations can be far greater than for unharvested forests in the long term via fossil fuel-substitution. [2,10]	sawlog/pulpwood rotations) where bioenergy harvest cycles are relatively short, eg. short rotation crops. [D] Removal of agricultural and forest residues has mitigation benefits, but the trade-off with removal of carbon from the ecosystem and impact on soil health, additional fertiliser input etc., needs to be quantified. Also, potential issue of negative Indirect Land Use Change impacts if conversion leads to reduced agricultural production in one region being offset by increased conversion of land elsewhere. [11]
Forest management - Sawlog plantations		No current CFI Methodology	Economic viability of plantations could be increased significantly if C sequestered in soil and wood products were credited. [D] One option for management could be to increase rotation lengths, which increases biomass production and decreases frequency of harvesting. These should increase SOC over time. [D]	Under current carbon accounting rules, (which excludes C in wood products and soil) establishment of new industrial plantations are generally not economically viable without a carbon payment of about \$10–30 t CO_2-e. [13] Even higher payments may be required to make extending rotation lengths economically viable.[13]

Abbreviations:

C - Carbon, CFI - Carbon Farming Initiative, CO_2 - Carbon dioxide, GHG - Greenhouse gas(es), N_2O - Nitrous oxide, SOC – Soil organic carbon

Table References

Lettered references indicates use of author/editors text or edits to tables 1-4 as follows:

A. Input from Dr. Fiona Robertson, (2014) Research Scientist – Department of Environment and Primary Industries

B. Input from Prof. Richard Eckard, Associate Professor with the Melbourne School of Land and Environment, The University of Melbourne.

C. Input from report by Sanderman, J., Farquharson, R., Baldock, J., (2010). Soil carbon sequestration potential: a review for Australian agriculture. CSIRO Sustainable Agriculture National Research Flagship. Table 4. p 49. ‘Summary of major management options for sequestering carbon in agricultural soils’.

D. Input from Dr. Keryn Paul, (2014) Research Scientist, Commonwealth Scientific and Industrial Research Organisation, (CSIRO).

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