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SYNERGIES BETWEEN CONVENTIONAL SOIL ORGANIC CARBON, FARM PRODUCTIVITY, SOIL SEQUESTRATION AND SOIL CARBON MARKET RISK IN AUSTRALIA

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ABTRACT

The investment risk of sequestering carbon as soil organic carbon (SOC) is low when compared to the susceptibility of forestry sequestration projects to disease, bushfires and droughts over a 100-year investment timeframe. As it can require decades to create a substantial carbon market asset with the slow natural accrual rates of carbon in soils, farmers will require short-term benefits to their conventional productivity from SOC additions. This chapter explores the additional effects of improving farm SOC levels on conventional farm productivity, soil nutrition, crop yields, soil water use efficiency, crop stability, disease resistance, soil biodiversity and tillage. This work also collates a broad range of management options available to farmers for utilising SOC to assist current productivity, while clarifying the risks and uncertainties of soil carbon stock fluxes, carbon markets and carbon emission policy developments in Australia.

INTRODUCTION

Perceived synergies between climate change mitigation and adaptation can increase the interest in certain technologies and practices that might not increase conventional productivity of the farm. Prospective mitigation and adaptation synergies require a detailed and comprehensive scientific foundation. In addition, these synergistic options require low economic and market risk, must be easily implemented, produce sufficient mitigation and adaptation benefits, and must be financially rewarding. Without reasonable availability of resources and scientific, policy and market investment certainty, it will be unlikely that farmers will be exposing their businesses to unacceptable levels of financial and market risk [1]. Therefore, without sufficient supporting empirical evidence, market-based farm mitigation and adaptation activities will entail too much farm investment risk to result in sizable sectoral decreases in emissions and vulnerability to climatic changes.

One prospective adaptation and mitigation synergy is to increase the soil organic carbon levels in agricultural lands [2]. The techniques used to increase carbon stocks are common natural resource management practices that farmers are likely to be familiar with. Research to date suggests that paddocks with higher levels of SOC show less long-term yield variability, are less sensitive to droughts, maintain good soil fertility, have higher cation exchange capacities, can reduce input costs, enhance trace element availability, reduce soil and wind erosion, and boost productivity. Therefore it is sensible to explore adaptation management practices that improve SOC stocks from a conventional perspective in addition to their potential value in climate change mitigation markets.

Adapting to variable climatic conditions is commonplace in Australia, as it has the highest inter-annual natural rainfall variability of all the continents. The principal cause of this natural variability is known as the El Niño/Southern Oscillation Index (ENSO), or the Southern Oscillation Index (SOI). Rainfall variability is the principal climatic factor that determines agricultural management in Australia, as yield is closely related to rainfall [3]. Farming systems that have been managed to enhance SOC show less long-term yield variability and are less sensitive to drought risk than conventionally managed farms [4]; [5]. Therefore, increasing farm stability and resilience to climate stresses by using scientifically verified SOC management practices can reduce uncertainties for Australian farmers in a natural and anthropogenically variable climate [6]; [7]; [8]; [9].

AGRICULTURAL GREENHOUSE GAS EMISSIONS & SOIL C

The natural variability of the Australian climate has resulted in Australia choosing to not account for Article 3.4 emissions in the Kyoto Target in the National Inventory Report to the United Nations Framework Convention on Climate Change. The Article 3.4 emissions omitted include all native forests under management, revegetation that does not meet forest criteria, and carbon stored in soil and vegetation on both grazing and crop lands [10]. Australian soil carbon is only reported for the Kyoto target as a component of land-use change activities under Article 3.3. The Article 3.4 emissions are excluded because of the risks associated with including large annual fluctuations due to climate dependent emissions (Figure 1).

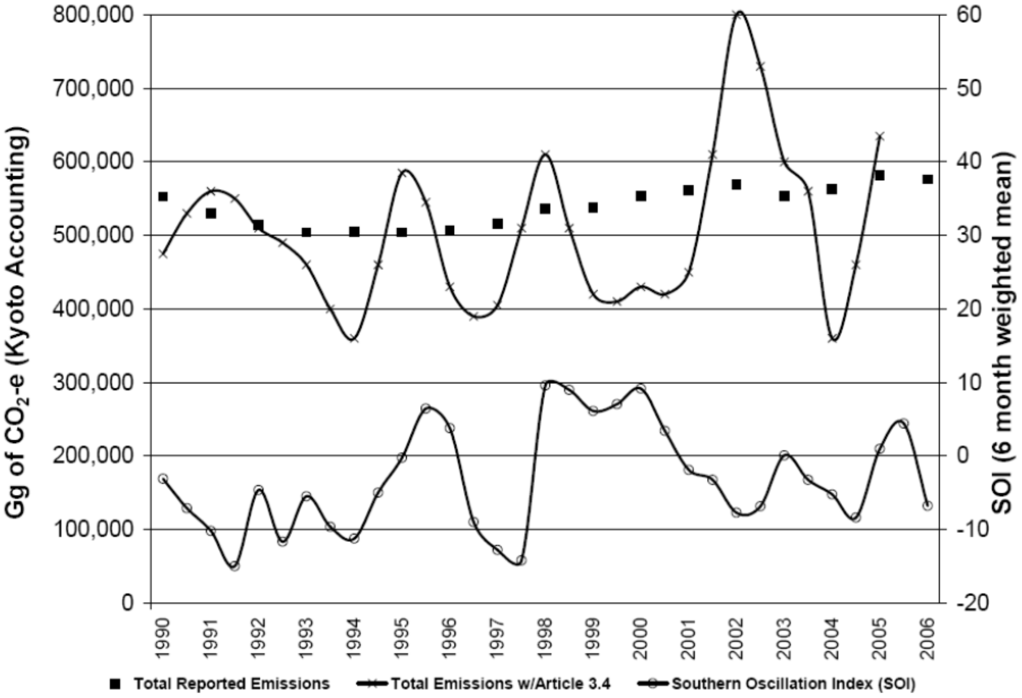


Figure 1: A comparison between Australia’s national reported Kyoto emissions, with and without Article 3.4 emissions and the Southern Oscillation Index (SOI).

Unlike most other sectors that emit greenhouse gasses, the agricultural sector emissions are mostly methane and nitrous oxide (Table 1). These emissions are predominantly from enteric fermentation in ruminants, prescribed burning and microbial activities in soil and water following fertiliser application. (Table 2).

Australian agricultural soil emission subcategories are comprised of the emissions from direct, indirect and animal production, available at the resolution of the States and the Northern Territory. In the State of Western Australia (WA), indirect emissions from fertilisers, manures and burning is the largest subcategory with slightly under half of the state's total agricultural soil emissions. WA's direct agricultural soil emissions from applying fertilisers, manures, nitrogen fixing crops and crop residues contribute around one-third of the total and the remaining emissions are from animal excretion on paddock. These emission totals, available from the National Greenhouse Gas Inventory (NGGI) for each year from 1990, shows the steady increase in emissions from this subcategory in WA (Figure 2). Reducing agricultural soil emissions in the NGGI requires farmers to be aware of the links between their specific management practices and the resulting direct and indirect emissions.

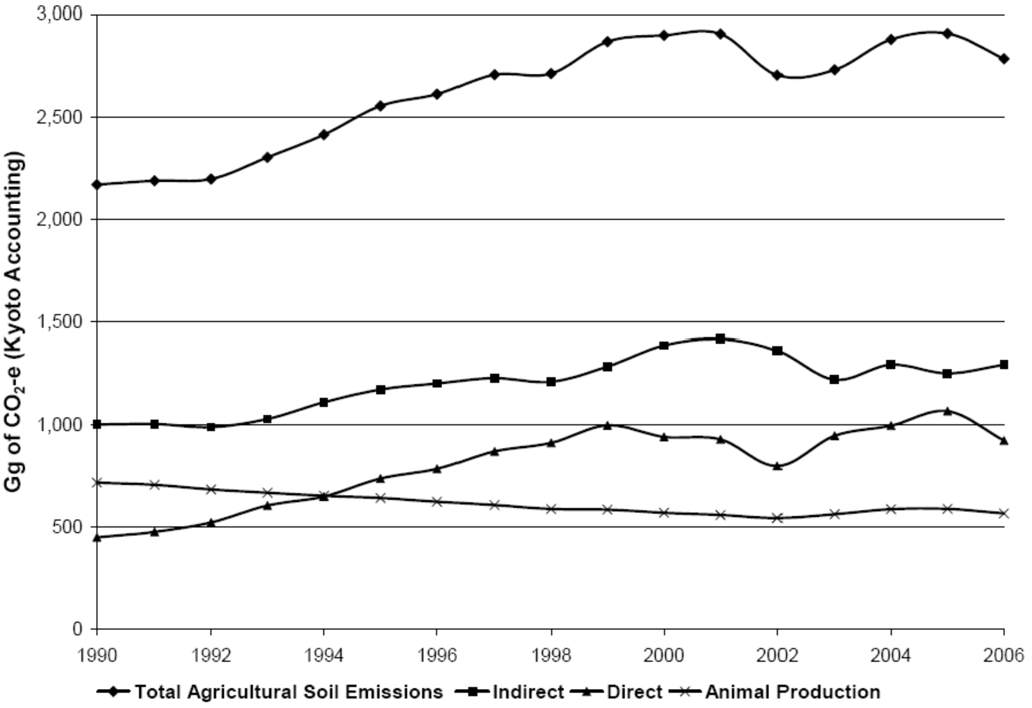
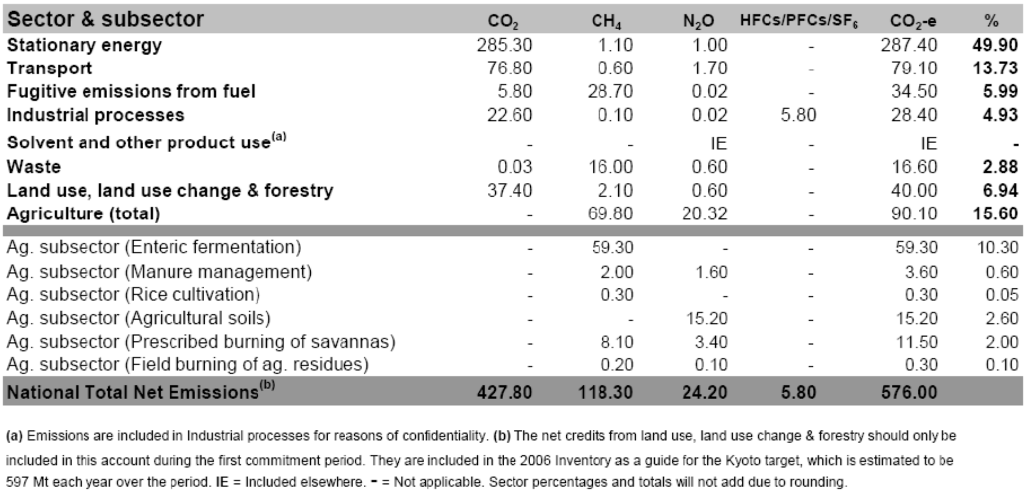


Figure 2: Western Australian agricultural soil emissions from 1990 to 2006.

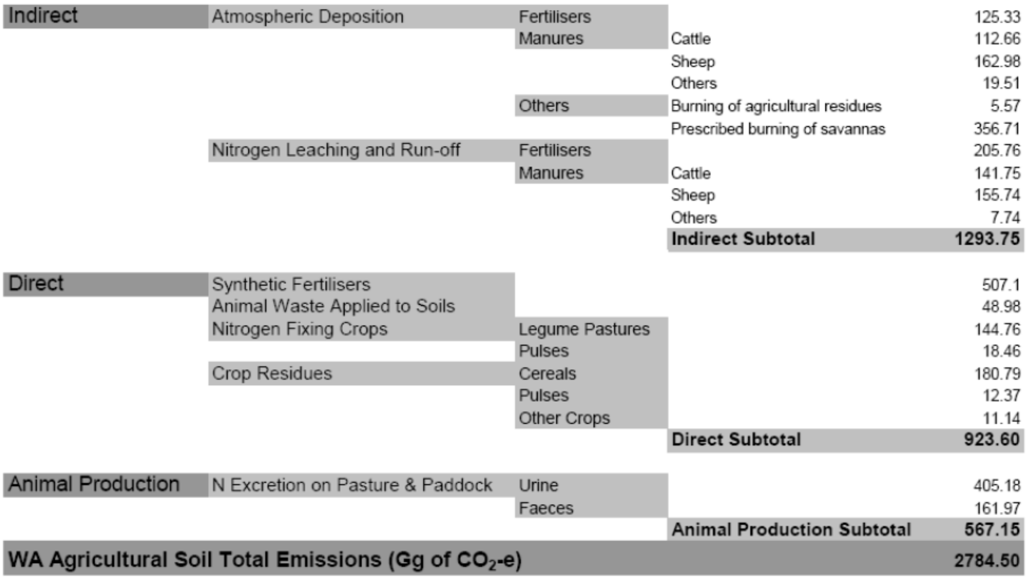
Table 1: Australian 2006 sectoral net greenhouse gas emissions (Mt, Kyoto accounting).



Sector & subsector	CO_2	CH_4	N_2O	$HFCs/PFCs/SF_6$	CO_2-e	%
Stationary energy	285.30	1.10	1.00	-	287.40	**49.90**
Transport	76.80	0.60	1.70	-	79.10	**13.73**
Fugitive emissions from fuel	5.80	28.70	0.02	-	34.50	**5.99**
Industrial processes	22.60	0.10	0.02	5.80	28.40	**4.93**
Solvent and other product use[(a)]	-	-	IE	-	IE	**-**
Waste	0.03	16.00	0.60	-	16.60	**2.88**
Land use, land use change & forestry	37.40	2.10	0.60	-	40.00	**6.94**
Agriculture (total)	-	69.80	20.32	-	90.10	**15.60**
Ag. subsector (Enteric fermentation)	-	59.30	-	-	59.30	10.30
Ag. subsector (Manure management)	-	2.00	1.60	-	3.60	0.60
Ag. subsector (Rice cultivation)	-	0.30	-	-	0.30	0.05
Ag. subsector (Agricultural soils)	-	-	15.20	-	15.20	2.60
Ag. subsector (Prescribed burning of savannas)	-	8.10	3.40	-	11.50	2.00
Ag. subsector (Field burning of ag. residues)	-	0.20	0.10	-	0.30	0.10
National Total Net Emissions[(b)]	**427.80**	**118.30**	**24.20**	**5.80**	**576.00**	

(a) Emissions are included in Industrial processes for reasons of confidentiality. **(b)** The net credits from land use, land use change & forestry should only be included in this account during the first commitment period. They are included in the 2006 Inventory as a guide for the Kyoto target, which is estimated to be 597 Mt each year over the period. **IE** = Included elsewhere. **-** = Not applicable. Sector percentages and totals will not add due to rounding.

Table 2: Western Australian 2006 agricultural soil emission subcategory totals (Gg, Kyoto accounting).



Indirect	Atmospheric Deposition	Fertilisers		125.33
		Manures	Cattle	112.66
			Sheep	162.98
			Others	19.51
		Others	Burning of agricultural residues	5.57
			Prescribed burning of savannas	356.71
	Nitrogen Leaching and Run-off	Fertilisers		205.76
		Manures	Cattle	141.75
			Sheep	155.74
			Others	7.74
			Indirect Subtotal	**1293.75**
Direct	Synthetic Fertilisers			507.1
	Animal Waste Applied to Soils			48.98
	Nitrogen Fixing Crops	Legume Pastures		144.76
		Pulses		18.46
	Crop Residues	Cereals		180.79
		Pulses		12.37
		Other Crops		11.14
			Direct Subtotal	**923.60**
Animal Production	N Excretion on Pasture & Paddock	Urine		405.18
		Faeces		161.97
			Animal Production Subtotal	**567.15**
WA Agricultural Soil Total Emissions (Gg of CO_2-e)				**2784.50**

What is meant by “direct” and “indirect” soil emission categories are sometimes a source of confusion when attempting to reduce overall emissions from farm activities, particularly with the use of fertilisers and manures. Manuring has a number of practical applications in agronomy, but net carbon sequestration is not one of them. This is because more SOC is produced in soils when crop residues are allowed to decompose than when they are fed to animals to produce manure. Nitrogen fertiliser is also commonly recommended to increase SOC. While this is true for local-scale farming in terms of reducing farm greenhouse gas emissions with the increase of SOC in the 0-30 cm of topsoil layers, the amount sequestered is insufficient to balance global emissions produced during fertiliser manufacture [11]. While pockets of practical and technical difficulties to successful soil sequestration remain, there is a need for parallel work on reducing political and market barriers to farmers using soils to generate offsets under emission trading schemes.

AGRICULTURAL SOC OFFSET MARKETS, POLICIES AND RISKS

Australia’s emission trading scheme, the Carbon Pollution Reduction Scheme (CPRS) explicitly advocates further research into both measuring and retaining carbon in soils to provide a comprehensive and scientifically accurate national carbon accounting methodology and monitoring [10]. Developing standardised methods of quantifying SOC offset project for specific land and soil-use changes streamlines the procedures involved in offset certification and verification. Unfortunately the use of standardised accounting methodologies without sufficient model verification will likely result in inadequate estimates of the actual sequestered carbon in soils. This inadequacy is likely result in discounting of soil carbon offsets in carbon trading markets to the point where Australian SOC offset projects will not occur.

Australian SOC offset products ineligible to be traded on the Chicago Climate Exchange (CCX) as the CCX does not have an existing protocol that allows Australian soil offsets to generate tradable Carbon Financial Instrument (CFI) contracts. Trading of Australian SOC offset CFI products will require researching carbon uptake from soils from various soil cultivation methods to a level similar to the CCXs existing North American Soils Protocol. As Australia does not include Article 3.4 emissions in the Kyoto reporting, there remains a possibility of eventually trading Australian soil-derived CFI’s on the CCX if a sound sampling methodology and a protocol is approved. Domestically, Greenhouse Friendly™ (GF), an Australian Government initiative was launched in 2001 to provide offset market consumers confidence by certifying voluntary offset products and services and through an independent verification process of Australian abatement projects. To date, there are no existing or prospective projects approved by GF that achieve abatement through the sequestration of carbon in soils. This is primarily due to problems associated with monitoring and verification procedures. If a reliable monitoring procedure is developed that meet independent verification requirements, the GF program does have the capacity to approve projects specialising in SOC sequestration using technologies that enhance soil organic carbon levels coupled with forestry projects.

Australia uses the Australian National Carbon Accounting System (NCAS) and the “Full Carbon Accounting Model” (FullCAM) to account for carbon stock changes based on land use management. FullCAM estimates and predicts all biomass, litter and soil carbon pools in forest and agricultural systems and for changes in major greenhouse gases, nitrogen cycling and human-induced land use practices. The soil carbon modelling inputs include the soil clay content, temperature, soil moisture content, plant and manure inputs, plant cover, in addition to microbes and multiple active soil pools [12]. If accredited verifiers for forestry projects use FullCAM to estimate the encapsulation of active pools to the inert soil carbon pool, the results will likely require an additional verification study to ensure the modelling concurs with what is occurring on-site. Therefore, despite some very detailed soil research and useful biomass-soil carbon flow modelling software, it is likely that both passive and active SOC sequestration to forestry projects will still require verification by sampling soils directly.

The Australian Department of Climate Change acknowledges there is much research and development required before a comprehensive modelled account of SOC is achieved for Australian forestry projects, soil management changes and direct biomass application to soils. For practical reasons national SOC stock accounts are modelled to reduce measurement requirements over vast spatial scales. These models still require substantial amounts of data including soil types, initial carbon content, clay component, land uses, climate, and residue inputs in addition to calibration and verification information. The NCAS soil carbon model validation results are generally very good, although their remain difficulties in reliably modelling changes in coarse woody debris and biomass litter turnover from input, transfers and loss information due the complexity of its dynamic nature in relation to soils [10]. At this stage it seems that direct sampling of SOC sequestration appears the least-risk option for project developers of enhanced SOC offsets.

Future developments in accounting and verification of direct soil sampling of passive and actively enhanced SOC pools will enable the creation of Verified Emission Reductions (VERs) under a methodology similar to the GF program. However, if Australian agriculture is captured in the CPRS, then it will severely limit the scope to create agricultural offsets and the incentives to further develop offset methodologies [10]. While the agricultural sector will not be included in the CPRS until at least 2015 (if at all), the uncertainty of how such a policy will capture the variety of farm activities and emissions has strong parallels with the current issues faced by the waste sector. In the future even without agricultural CPRS capture, large piggery and dairy waste recovery activities, including biogas renewable energy generation options, may have a similar liability under a CPRS akin to the waste recovery sector. Agriculturalists would be well advised to follow the developments of how waste recovery facilities handle the introduction of the CPRS, which is expected to occur around 2010, as the two sectoral emission profiles and resources managed are largely biologically derived.

There are also strong parallels between the external risks faced by early adopters of mitigation options in the waste and agricultural sectors from Australian Government policy changes relating to CPRS capture. The Australian and New Zealand Standard Industrial Classification (ANZSIC) titles and codes are used to collect and publish statistical information in the two countries. The ANZSIC codes will be used to determine businesses that are captured under the Australian CPRS, and currently large domestic biomass waste-to-compost manufacturers will be included. In Western Australia, the South Metropolitan Regional

Council’s Regional Resource Recovery Centre (RRRC) is a GF approved integrated waste processing facility abatement project. The RRRC produces significant useful biomass as it diverts and recovers 85% of domestic waste from landfill to produce compost, mulch or is separated and delivered to manufacturers for recycling. The RRRC processing capacity includes 169,000 t for various biomass inputs in addition to 30,000 t of materials recovery for co-mingled recyclables [13]. Existing waste recovery abatement activities that generate VERs might become unprofitable if they attract liabilities under the CPRS. Without being able to offset their own financial liabilities by generating undiscounted SOC VERs, waste recovery projects might be the unfortunate looser under some CPRS capture scenarios. The RRRC currently generates 80,000 VERs annually from their waste recovery activities and their customers that voluntarily offset their emissions include Origin Energy, Virgin Blue, BP, Synergy, the Carbon Reduction Institute, the Australian Climate Exchange and others. The financial impact for entities unable to sell these offsets if their operations exceed 25,000 tCO_2-e in a financial year under a future CPRS, will also attract the administration costs associated with its implementation.

CPRS administration costs are likely to be similar to the costs of independently assessing VERs under the GF program. To become an approved generator of VERs, the original RRRC GF project design document for the RRRC included a ballpark AUD$20,000 consultancy with ongoing annual reporting requirements costing around AUD$15,000 for the independent verification process. The RRRC does not currently receive VERs for the additional SOC that any biomass compost sequesters, only the avoided emissions from not sending the waste to landfill. If facilities such as the RRRC are captured under the CPRS, the activities and emissions that are counted in such a scheme can quickly become complex. Additional difficulty result from the variety of waste processing options available and the choice of which point in the processing cycle the emissions or offsets may be acquitted against liabilities. As net life-cycle emissions from composting abates around 50 kg of CO_2-e per tonne of composted yard trimmings and food waste, the additional soil sequestration combined with the improved tree growth seems like a win-win situation for forestry projects and biomass waste-to-compost facilities wishing to increase abatement. However, who owns the carbon rights to the compost may become an issue. Sidestepping these issues may require alternatives to composting biomass such as directly combusting the waste. This combustion also reduces net CO_2-e life-cycle emissions of yard trimmings and food waste by 60 and 50 kg of CO_2-e per tonne respectively [14]. If pyrolysis technologies were used instead of complete combustion options, the waste biomass could be converted to carbon-dense stable form of charcoal for use as a valuable soil conditioner. Using these technologies, around half of the carbon in the biomass may be sequestered while generating roughly two-thirds of the bioenergy of the complete combustion electricity generation option [15]. The question of when emissions are accounted for under the CPRS and/or who owns the right to the carbon and is left holding a liability remains open for now.

If agriculture is likely to be captured after 2015, then there will be little incentive to develop offset methodologies and institutional infrastructure to support an offset market for such a short period. The final decision of whether agriculture is included in the CPRS (expected in 2013), will also determine the existence of a formal agricultural offset scheme [10]. Even without agricultural CPRS capture, sequestering carbon in soils does not come without market risk. For example, if an offset business sold VERs in the beginning of 2008 that are required to be maintained for 100 years, and this offset was either removed or was proven to be non-existent, then the business would be liable to either replace the offset or purchase VERs to cover any shortfall. With the expected increases in carbon prices over-time, the financial risk of selling SOC VERs prematurely at discounted market prices, using unverified models are high. To illustrate the issue, if the RRRC was required to repurchase their 2007 VERs traded on the Australian Climate Exchange (ACX) only one year after selling them, they would need to pay an additional 30% (excluding transaction costs) due to the rising market value of their VERs between 2007 and 2008 (Figure 3). With the price of carbon generally expected to increase over time, the financial risk of prematurely selling VERs that require long-term maintenance is a risk that may be preventing mitigation projects from being developed further.

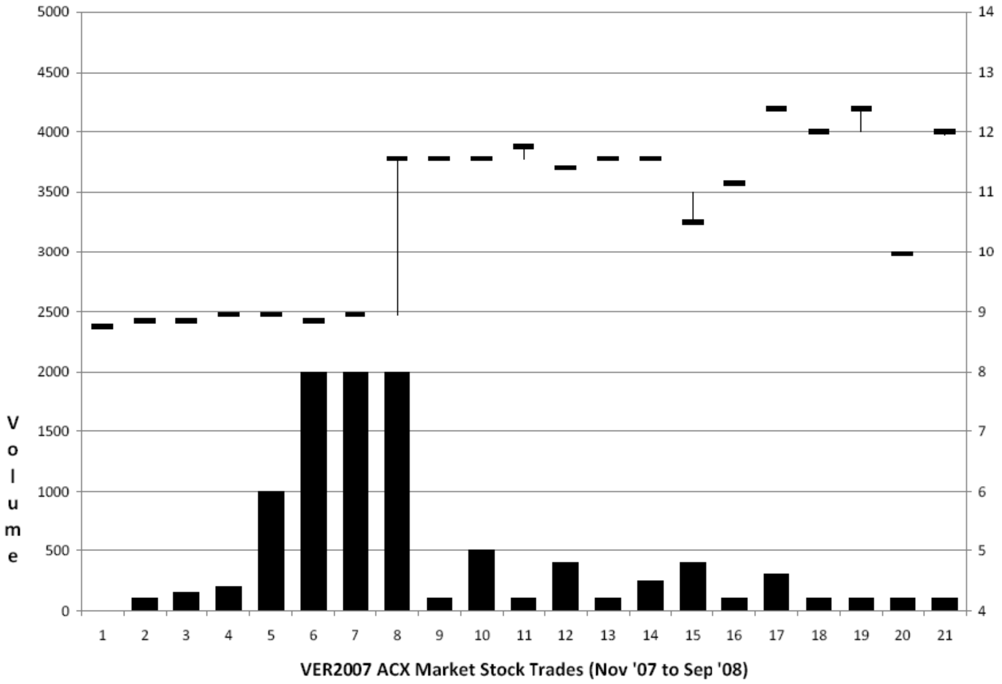


Figure 3: Total VER2007 product trade price and volume on the Australian Climate Exchange.

SOC MANGEMENT TO DECREASE LIABILITIES AND INCREASE PRODUCTIVITY

The global decline in SOC as a result of deforestation and arable cropping have made significant contributions to increased levels of atmospheric carbon dioxide [16] as cited in [17]. As a result of climate change mitigation policies there is renewed interest in the role of agricultural soils in reducing emissions and enhancing biological carbon sequestration. Returning SOC back into the soil gives farmers an indication of how it affects their primary productivity, while monitoring future SOC carbon market developments. Farms already using economically efficient practices, may receive lower financial returns if they prematurely attempt to sequester carbon. For farmers to avoid this income opportunity cost they should understand their soil emissions, it’s sequestration potential and the appropriate management practices that enhance their farms productivity to decrease the market risks of trading in sequestered soil carbon [18].

SOC, FARM NUTRIENT AVAILABILITY AND WATER USE EFFICIENCY

Managing pasture soils to increase carbon levels increase cation exchange capacities and enhance availability of trace elements [19]; [20]. The ability of soils to retain nutrients in cation forms that are available to plants is known to increase in proportion with soil organic matter [21]. High nutrient use efficiencies occur when a farmer can obtain large amounts of plant growth from soils with low nutrient levels [9]. As a general rule, when carbon in soils is lost, nitrogen is often also lost and when carbon is gained, nitrogen is also gained [22]. Increasing the ability of pastures to use nitrogen and nutrients can reduce the expenditures required for fertilisers and soil conditioners. The balance of organic matter production and its decomposition by soil organisms determines SOC stock levels. Both of these processes are strongly dependent on physical, chemical and biological factors such as the climate, nutrient availability, plant growth patterns, and soil water status [23]; [24].

In some circumstances the build up of repellent organic matter in sandy soils can slow water penetration into dry soils. Water repellency is common in annual cropping systems, but has also been reported to increase under long-term lucerne and veldt grass stands [25] as cited by [26]. Due to the lack of water in the soil in early summer, productivity declines in the southwest jarrah forest regions of Western Australia (WA). Maximum productivity occurs in the late winter to early spring due to the replenishing winter rains [27]. Reducing the level of evaporation will conserve soil water in the early growing season, while a reduction in evaporation later in the season can improve plant water use efficiency by extending the season [28]. Increasing SOC stocks can lower soil bulk densities to allow greater water penetration and improve water-use efficiency to increase pasture productivity [19]; [20]. Maintaining some water in the soil up to harvest can control soil loss, as higher moisture at harvest leads to less soil erosion [29]. Maintaining soil nutrients, reducing fallow times and practicing no-tillage will also enhance water storage and water use efficiency [30]; [31]. Composting and green manures improve soil structure through reducing erosion and evaporation, protects against raindrop impact and increases the SOC stocks, and in some circumstances is an alternative to herbicide use. Composts and mulches also modify temperature and moisture and the effects are linked to the quality and quantity of the biomass residues [32].

PASTURE TYPES AND THEIR EFFECTS ON C SOIL STOCKS

Maintaining plant cover throughout the year is probably the most important factor that influences how much soil is lost by both water and wind erosion [26]. As perennials are not required to germinate each year, their deeply penetrating roots create biopores and improve soil structure and drainage which can reduce problems with water repellence [26]. Deep-rooted perennials can use water when annual pastures are dead, recover leached nitrate, reduce acidification and provide a soil cover and root mass to restrict wind and water erosion as many perennial pastures persist through summer [26]; [33]. Ferdowsian and Greenham (1992) found that annual pastures in the southwest of WA had few roots penetrating deeper than half a metre. They found that phalaris and yorkshire fog roots extended to one metre, and kikuyu roots had the largest root mass, extending below one metre. The deeper rooting habit of plants such as phalaris and tall fescue offer more scope for overcoming degraded soils than cocksfoot and perennial ryegrass, while kikuyu remains green and productive throughout summer [26]. Because of their deeper and denser root systems, perennial forage species are generally more competitive with tree windbreaks in comparison to annual crops [34].

Trees and shrubs improve the soil nutrient cycle by introducing deeper root systems which cycle nutrients from deeper layers of soil into top soils to a greater extent than annuals [35]. Shading of the soil by perennial pastures also reduces the rate of organic matter decomposition, which increases SOC stocks and associated benefits [35]. A study by Resh, Binkley and Parrotta (2002) on nitrogen fixing perennial trees showed that the levels of SOC under the nitrogen fixers was between 10 and 90 % greater than the soil under eucalyptus trees. The greater SOC levels under the nitrogen fixing trees resulted from both the greater retention of old SOC and the greater accretion of new SOC [36].

A combination of perennial grasses and trees can also reduce runoff, with kikuyu and subterranean clover often used for this purpose as both are also shade tolerant [34]. Nitrate accumulates when subterranean clover plants break down in summer and leaches from the soil profile in annual pastures following the autumn rains. This can occur before annual pastures can develop an actively growing root system that captures significant levels of nitrate [37]. Nutrient topdressing in autumn before an annual pasture develops active roots systems or sufficient plant cover often results in both fertiliser and topsoil loss with opening rains. One autumn storm in Albany, on the south coast of WA, up to 60% of the applied phosphorous was lost in particulate form [38] as cited in [26].

One example of a detrimental pasture management practice is the permanent removal of crop residues over summer. The removal of biomass is inversely related to SOC accumulation, as the remaining biomass eventually decomposes and contributes to SOC and nutrient levels [39]. High intensity grazing can limit the amount of plant growth and surface cover, which has a negative effect on SOC stocks and the total fodder available over the growing season. However, leaving some crop residues in place and reducing summer grazing intensity will reduce available feed and the relative costs and benefits of reduced stock ratios will require consideration by farmers. At this time, more research is required to link specific combinations of grazing management practices to increased feed productivity and soil carbon stocks in particular climates [40]. The main constraints to the adoption of perennial pastures are the perceived costs and their poor persistence under continuous grazing, especially by sheep [26]. Nonetheless, it is likely that temperate perennial grasses, in conjunction with legumes, could provide a sustainable pasture base in southern Australia, if animal grazing is well managed [26].

The inclusion of perennial forages in rotations increases soil carbon levels relative to rotations with annual crops alone [30]. Continuous and diverse pasture growth and grazing most closely simulates perennial systems that lead to minimal nutrient losses and maximum accumulation biological organisms [31]. Soil carbon levels also tend to increase with crop rotations, continuous cropping, cover crops and mixed cropping [30]; [31]; [32]. Rotations of crops are an effective management strategy for annual monocultures and cover cropping assists orchards and vineyards to achieve greater levels of biodiversity and stability. Orchard cover crops are commonly and successfully used to fix nitrogen, modify the microclimate, add SOC, provide a habitat for beneficial insects and encourage soil biology [19].

SOIL BIODIVERSITY, CROP STABLITY AND DISEASE RESISTANCE

Most of the biodiversity of agricultural systems resides in the soil, but our understanding of this biodiversity is generally poor [41]. Biodiversity comprises the “planned” biodiversity, such as the crops and/or livestock the farmer wishes to produce, as well as the “unplanned” biodiversity, which is all other biota in the system. The value of the aboveground planned biodiversity is more obvious to the observer than the intrinsic value of the soil biodiversity below our feet. In addition, most biological organisms are treated and viewed as harmful (pathogens, pests and weeds), but many are in fact beneficial (pollinating insects and pest predators). They therefore should be either managed to increase or decrease their populations based on their individual merit. Unfortunately, the management of soil biodiversity is not as simple as choosing livestock and crop varieties [9].

Increased soil biota assists biological immobilisation of inorganic nitrogen which also aids in retaining nitrogen, adsorbs dissolved ammonium, nitrate, phosphate, as well as water repellent organic pollutants [42]; [43]; [44]; [45]; [15]. Food-web interactions between soil biota and plant roots also have a large effect on SOC fixation, crop quality, pest predators, beneficial organisms that cycle nutrients, and the incidence of soil-borne plant and animal pests and diseases [9]. Resistance against outbreaks of pests and diseases, and resilience from disturbance is of particular importance to agricultural crops [46]. High total microbial biomass and a high competition for carbon and nutrients leads to the suppression of specific pathogens by particular competitors operating in a background of general competition [9]; [19]. Increasing soil biodiversity for crop resilience against stress and disturbance can be regarded as a form of natural protective insurance [9]. Stability is often defined as the ability to recover from stress or disturbance, whereas resilience refers to the rate with which populations recover from stress or disturbance [6]; [7]; [9]. A short-term transient event is known as a “disturbance” where a more persistent pressure, such as a heavy metal contamination that continuously affects the organisms is referred to as a “stress” [47]; [9].

Experiments undertaken by Griffiths *et al.* (2000) on the relationship between stresses, and disturbances on biodiversity and ecosystem functioning showed that high and low soil biodiversities recover from stresses at different rates. This research involved creating stresses such as temperature extremes, toxic chemicals and particular minerals. High soil biodiversities were associated with a greater resumption of normal ecological functions to pre-stress levels after the loss of some populations. These experimental results showed that even though stressed soils showed a significant reduction in biodiversity, the ecological functions they performed was only mildly affected. Interestingly, when these same stressed soils were compared with similar unstressed soils, both undergoing another disturbance event, the ecological functions were more severely affected, and for a longer time in the stressed groups than the unstressed soil groups [6]; [9]. Therefore, the response of the microbial communities to stressors depends on the history of the organisms and the type of stressor applied [48]; [7]; [49]. Biodiversity does not necessarily confer ecological function stability, but does result in a higher resilience and an ability to recover quickly from disturbances [9]; [7].

Soil biodiversity is more meaningful to farmers when integrated with aboveground productivity in agricultural systems. One of the most well known uses of soil organisms in agriculture is to fix nitrogen from the air into the soils. Biological nitrogen fixation is provided by soil biota in leguminous plants and may fix more than 100 kg of nitrogen per hectare per year. Total annual contribution of nitrogen by micro-organisms in both agricultural and natural ecosystems has been estimated at between 140 to 170 million tonnes annually, valued at US$ 90 billion per year. Other useful soil biota functions and their estimated annual values are: recycling of organic wastes, bio-remediation of polluted soils and water (US$ 121 billion); the control of pests in agricultural systems (US$160 billion); the use of various wild insects, plant roots and mushrooms as food for humans ($US 180 billion); and the pollination of plants by insects that spend a critical stage of their life within the soil (US$ 200 billion) [9].

BIOLOGICAL MANAGEMENT IN PASTURE AND SOILS

Farm management options that improve soil biological processes, increase biodiversity and sustain viable community of soil biota include: increasing the amount and/or quality of organic residues; using biological control for pests and diseases; inoculating for beneficial soil organisms such as disease antagonists, microsymbionts, rhizobacteria; minimising soil disturbance, pesticide use, irrigation and artificial fertilisers, and; using earthworms for disease control and soil fertility [9]. Under some conditions fertiliser applications may decrease SOC and soil microbial populations, but the beneficial effects of fertilisers generally offset any adverse affects as increased plant residues increase microbial activity [32]. Microbial activity is highest in organically fertilised agricultural soils and manure applications tend to increase the earthworm biomass in cropped soils, while reduced tillage creates a more stable environment [19]. Tillage disrupts soil aggregates, compacts soils and disturbs plant and animal communities that contribute to aggregation and leads to lower microbial activity [32]. Herbicide residue can negatively effect soil biodiversity by changing the soil microclimate [19]. A two-year study by Caldeira and colleagues (2001) on soil moisture, water availability, and water use by plants in various soil biodiversities found significantly higher total biomass in species-rich areas alongside a reduction in water consumption, when compared to monocultures. The results suggested that the species-rich plant communities had more water available in the upper soil where the roots were concentrated. In the majority of seasons, soil polycultures significantly increased the uptake efficiency of nitrogen and phosphorus relative to monocultures, which some research suggests may be due the soil biota and soil biodiversity [9].

A microcosm study by Heemsbergen and colleagues (2004) showed that it may not be general biodiversity that enhances soil nutrient supply, but the functional and evolutionary dissimilarity of soil organism species [50]; [9]. Increasing soil mycorrhizal fungal diversity is also associated with increased water uptake efficiency and may be indirect such as mycorrhiza-mediated effects on soil structure [9]. Auge (2004) showed that the effect of mycorrhizal fungi on stomatal conductance was approximately equally due to root and soil colonisation. Therefore even plants without the fungi colonies benefit from mycorrhizal fungi water uptake and the increased soil moisture availability to sustain longer periods of biomass growth, and as a consequence SOC fixation [51]; [9].

In the case of agroecosystems and soils, the objective is to maintain key functional groups and therefore it is required to know if key species exist, what they are, and how many are necessary to sustain soil processes and primary crop productivity. Testing soils for biological diversity may even become a cheap and widely available tool to more accurately monitor system changes, as organism populations reflect specific characteristics of soils and SOC stocks [50]. Nonetheless, there is much more research needed to validate biological assessment and management practices suited to specific agro-ecosystems in Australian soils and climates [9].

TILLAGE AND CARBON STOCKS

Conventional tillage consists of disking, chiselling, ridging and residue incorporation into soil, while no-tillage methods leave crop residues on the soil surface [52]. Conventional tillage contributes to soil disturbance and is associated with more traditional cropping practices [53]. Losses of SOC of as much as 50% in surface soils (up to 20 cm depth) have been observed after cultivation for 30-50 years, with reductions averaging around 30% for the top one metre [54]. The effect of tillage in higher rainfall areas is greater than in areas with lower rainfall as water is less of a limiting factor in terms of plant growth [40]. For mean annual temperatures between 12.8 and 17.4 degrees Celsius, where average rainfall is higher than around 650 mm, soil management practices have a definite effect on SOC carbon density up to 30 cm, with higher densities corresponding to lower tillage and stubble retention [53]; [40]. The magnitude of difference between minimum disturbance methods on SOC densities have been found to be around 57 tonnes per hectare (t/ha), compared to nearby farms using conventional tillage practices, resulting in 43 t/ha up to 30 cm soil depths [40].

Tillage, in addition to mixing and stirring of soils, breaks up aggregates and exposes surfaces otherwise inaccessible to decomposers [54]. Conservation tillage practices are associated with reduced, or no soil disturbance, and include practices ranging from “no-tillage/direct drill” to “reduced tillage/minimum tillage” [40]. The use of no-till can increase SOC stocks in annual crop systems, provided that crop production is not adversely affected [30]. No-tillage or direct drill systems are those in which stubble is retained for the maximum length of time prior to sowing a new crop. Ground disturbance is kept to a minimum during sowing and seedbeds are not tilled prior to sowing. Permanent beds, raised beds, controlled traffic and precision agriculture are also grouped under the no-tillage classification [40].

Reduced tillage aims to minimise soil disturbance, while achieving a viable seedbed. As with no-tillage systems, weeds are controlled by herbicide and grazing and crop stubble is often burnt and/or incorporated into the soil. Farmers using reduce tillage often utilise implements that minimise the area, depth and extent of soil disturbance on the soil structure [40]. A study by Wright, Dou and Hons (2007), on SOC and nitrogen after 20 years of conservation tillage, found that the use of conventional tillage did not increase the SOC or total nitrogen in subsurface soils to levels greater than no tillage. The study suggested that burial or incorporation of residues was ineffective at increasing SOC or nitrogen accumulation over the 20-year period [52].

Wright *et al.* (2007) found conventional tillage reduced dissolved organic carbon, SOC and total nitrogen in surface soils (0-5 cm) under continuous wheat crops and in subsurface soil depths down to 55 cm for more intensive cropping sequences. No-tillage increased SOC, dissolved organic carbon and total nitrogen, compared to conventional tillage by 28, 18 and 33% respectively. High intensity non-monoculture cropping sequences, coupled with no-tillage resulted in the highest SOC stocks in subsurface soils, demonstrating the importance of subsurface carbon and nitrogen for potential carbon geosequestration. For more intensive cropping sequences under no-tillage, decreasing fallow periods and increasing crop residue production increased SOC and nitrogen levels to the 55 cm depth [52]. Therefore long-term conservation tillage may include protection of SOC and total nitrogen in subsurface soils and should assist in maintaining farm carbon stocks [53]; [52].

A report on the NCAS by Valzano, Murphy and Koen (2005), focussed on the impact of tillage on changes in SOC density in Australia. They found that changing from moderate to low intensity grazing, when in combination with any cropping tillage practice, would usually lead to a loss of SOC. The report stated that tillage practices alone are not sufficient to predict likely soil carbon densities as the set of management practices included in “low tillage” or “no-tillage” umbrellas range widely, especially in terms of the timing of various management practices in a season [40]. The NCAS report found the differential between conventional tillage practices and reduced tillage on paddock SOC densities was up to 10 t/ha. Interestingly, this difference was not apparent in the top 10 cm of soil. The report recorded differences of up to 25% between conventional tillage practices and conservation tillage, with the greatest SOC losses occurring with higher levels of soil disturbance in combination with stubble burning. Stubble burning was a traditional method used in late summer after harvest. At present, if stubble is burnt at all, it is now burnt just prior to sowing when fire restrictions are lifted, which is usually around March in the southern half of WA [40]. This reduces the likelihood of bushfires and reduced the times that soils are exposed to ambient conditions and erosion.

Crop stubble may be burnt, grazed or incorporated in either conservation or conventional tillage systems. Stubble incorporation involves the use of tillage implements to bury remnant plant residues and has traditionally been used to return organic matter to the soil and to protect from erosion. The NCAS report suggested that incorporation can transfer pathogens to other paddocks, offer less protection than stubble retention practices and can destroy soil structure and porosity [40]. Stubble retention involves leaving crop residues at the soil surface, which can be grazed just prior to sowing another crop. The report suggested that stubble retention is the best stubble management method, as it protects the soil surface from erosion and retains carbon at the soil surface [53]; [40].

CONCLUSION

Modulating farm yields while decreasing the required level of conventional farm inputs can decrease uncertainty, especially in periods of rising costs, labour shortages and climate change. The effective management of soil organic carbon (SOC) can influence soil fertility and soil physical properties such as aggregate stability and water holding capacity to improve the farm ecosystem [55]. The cultivation of an effective soil ecology can reduce fertiliser requirements, improve water use efficiency and prevent plant and nutritional deficiencies [30]; [19]; [31]; [9]; [20]; [21]. Despite these benefits, soil organic carbon is not routinely included in basic soil testing regimes in Australian agriculture, nor does it receive the recognition it deserves as a means for greenhouse gas mitigation.

Carbon sequestration in agricultural soils has the potential to create an economic commodity for farmers while improving conventional productivity and providing ecological benefits [1]. However, even using supposedly helpful pasture combinations, tillage practices and grazing levels, SOC densities can remain low given certain combinations of climate, soil type and past management practices [40]. More research and communication of farm soil management practices that build up SOC stocks for specific agricultural systems and combinations of climate and soil types is required to provide sufficient certainty to carbon markets in Australia. This primary research requires parallel policy and accounting methodology development to provide security to both farmers and investors for soil carbon product transactions.

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