

Filling the Research Gap

The National Soil Carbon Program

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Introduction

The Australian Government's \$14.23 million National Soil Carbon Program (NSCP) was developed to coordinate a national research network that would identify the most effective and practical strategies for managing soil carbon in Australian agricultural systems.

The NSCP provided high-level coordination and scientific leadership of the research projects on soil carbon under Round One of *Filling the Research Gap*. The NSCP research projects addressed two research priorities: increasing soil carbon and improving modelling capability.

Vast in scope and collaborative in execution, the program integrated research and development activities across a range of research providers, including CSIRO, state agencies and universities. The NSCP projects established strong links across projects under *Filling the Research Gap* and the associated *Carbon Farming Futures Program, Action on the Ground and Extension and Outreach, including the Climate Change Research Strategy for the Primary Industries (CCRSPI)*.

This report presents the key findings from the NSCP under four themes critical to soil carbon in Australian agricultural soils.

1. **Vegetation management** looked at the role of perennial vegetation in the management of soil carbon.
2. **Soil amendments** examined the potential for organic additions to soil to build soil carbon and the subsequent effect on greenhouse gas balance.
3. **Improved measurement** studied temporal changes in soil carbon to improve the capabilities of the existing models of soil carbon dynamics and support low-cost methods for measuring soil carbon.
4. **Management practices** looked at the effect of crop, pasture and forestry management practices on soil carbon.

A key to the program's success was developing an understanding of how to deliver the most practical strategies to reach an optimal increase in soil carbon while maintaining productivity and profitability in Australian agricultural systems.

The projects delivered high-quality data for a number of major agricultural and forestry systems – often for the first time – and supported advances in the Carbon Farming Initiative–Emissions Reduction Fund (CFI/ERF) scheme.

Major NSCP findings and contributions include:

- development of optimal soil sampling techniques for agriculture and forestry, and standardised methods for analysing soil organic carbon
- estimates of soil carbon for regrowth, reforestation and environmental and tagasaste (tree lucerne) plantings for the expansion of existing Emissions Fund Reduction carbon offsets
- new techniques for field estimation of soil organic carbon that have the potential to reduce sampling and analysis costs
- promising increases in crop productivity from the application of compost and biochar mix
- increased understanding of how cropping history affects the extent of soil organic carbon increase by shifting to pasture and reforestation



- improved knowledge of how ground cover provides carbon and landscape stability in grazing lands
- enhanced understanding of carbon (and nitrogen) as a component of soil organic matter for a better environment, and improved fertility and plant productivity for food, fibre and energy.

Highlights of the research findings

The NSCP findings have promising implications for landholders, industry and policymakers around improved carbon management. In addition, the projects delivered a wealth of information supporting management of the wider soil resource, greenhouse gas abatement and long-term land use sustainability.

Vegetation management

Landholders can potentially gain carbon credits – through the extension of existing carbon accounting methods – by incorporating biomass, litter from reforestation, regrowth and environmental plantings, including tagasaste (a forage legume).

NSCP projects made a substantial contribution to the process of understanding carbon as a component of soil organic matter for the restoration of landscapes, a better environment and improved soil fertility. Understanding carbon (and nitrogen) is critical to the increasing productivity of food, fibre and energy from the Australian land.

The projects on reforestation, environmental plantings and grazing lands facilitated superior new soil sampling designs. By improving their understanding of the sampling intensities required, researchers minimised uncertainty in soil carbon estimates under both forestry and agricultural systems.

Facilitated forest regrowth, reforestation and tree or shrub plantings increase grass production and provide shade for livestock in grazing systems. The challenge remains to develop best management practices that balance animal production with soil carbon benefits.

Vegetation management for soil organic carbon provides additional benefits through landscape remediation. These include: riparian plantings to improve water quality; plantings in saline or waterlogged paddocks; reforestation on degraded lands; tagasaste plantings to reduce salinity downslopes; biodiversity benefits; and sustainability, by decreasing soil loss via erosion and improving soil physical and chemical properties.

Soil amendments

- Consistent yield increases were recorded in field trials from compost and biochar used in combination for sugarcane, banana, maize, papaya and peanut crops in northern Queensland.

- Soil amendments such as biochar increase soil organic carbon sequestration significantly, and manures and composts marginally.
- Organic amendments increase the stocks of soil carbon and many amendments such as composts and manures are a good source of plant nutrients. Applying these amendments ensures sustainable land use and increased productivity, however, availability is limited, and transport and application costs may be substantial.

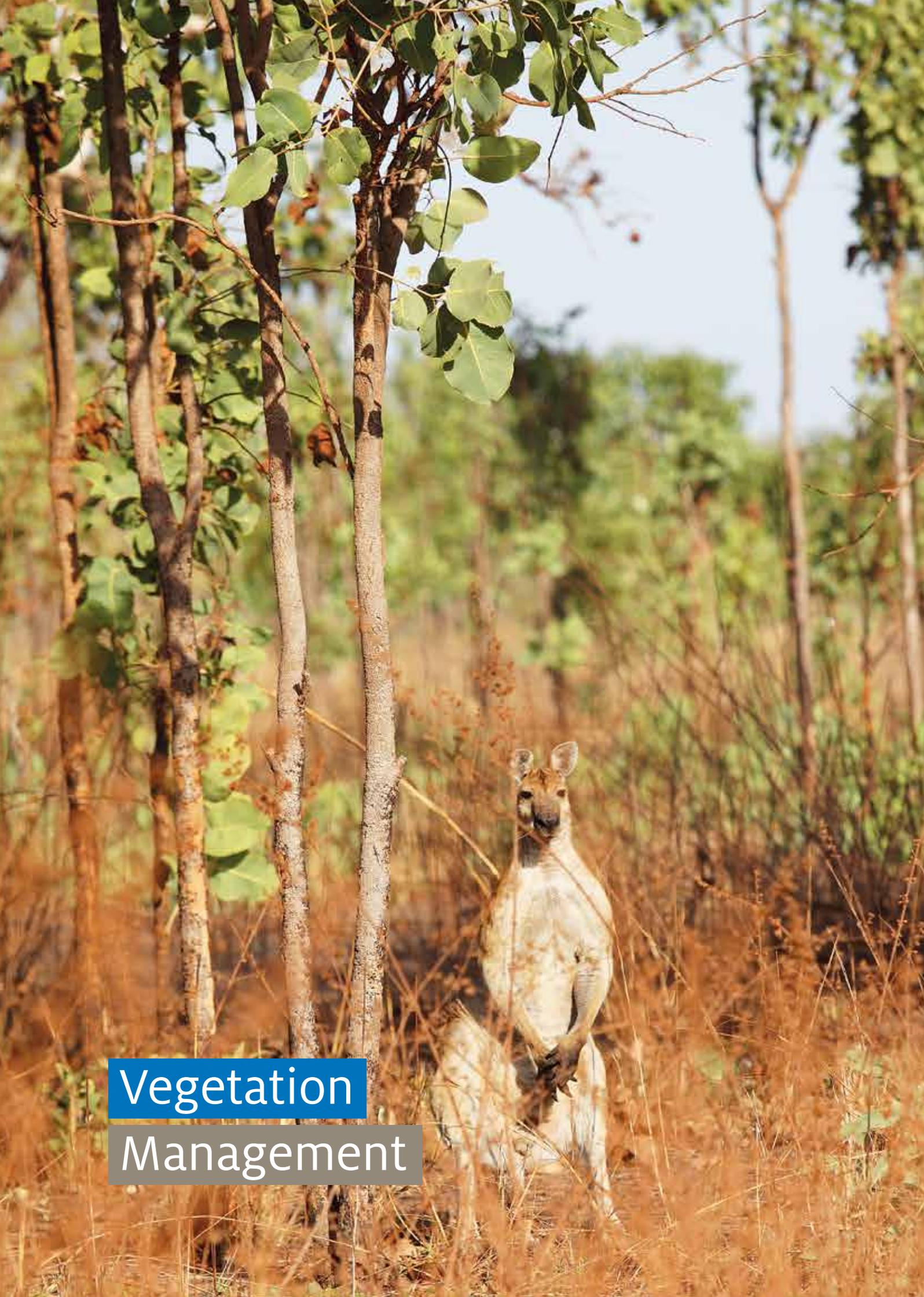
Improved measurement

- Sampling and analysing soil carbon and other soil specifications is a vital decision-making tool for landholders; however, cost can be a deterrent. The NSCP projects as well as legacy datasets used existing models – including FullCAM, RothC, APSIM and Century-DayCent – to reduce the monitoring costs of soil carbon for landholders.
- On-the-go *in situ* near infra-red (NIR) field estimation of soil organic carbon stocks in grazing lands (including rangelands and forestry) also has the potential to reduce the cost of soil organic carbon monitoring.
- The ability to rapidly assess various organic amendments using mid infra-red (MIR) and NIR spectroscopy provided datasets for FullCAM. There are now plans to develop this into an ERF methodology for carbon offsets.

Management practices

- Conversion of land use from cropping to pasture increases soil organic carbon stocks by as much as 0.2 tonnes carbon/ha per year. In improved pastures with fertiliser inputs and/or introduced legumes, sequestration rates may be even higher.
- The NSCP projects contributed to the development of the methodology of the CFI/ERF in relation to no-till, residue retention and fertiliser applications.
- A potential methodology for rangelands takes into account the total grazing pressure (both stock and non-stock animals) rather than domestic livestock only.
- In general, land use change from cropping to pasture (especially on marginal lands) improves the long-term productivity of that land.
- Retention of crop residues and plant matter provides ground cover, which is essential to reduce soil erosion and soil organic carbon loss by water or wind erosion, and contributes to sustainable land use.

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Vegetation
Management



Managed native forest regrowth

Soil carbon increase through rangeland restoration by facilitating native forest regrowth

The *Managed native forest regrowth* project assessed the stocks and turnover of soil organic carbon in regrowth up to 58 years old in previously cleared Queensland rangelands. It grew out of an increased interest in native forest regrowth, land use and carbon management, where soil organic carbon remains a source of uncertainty for estimation of carbon stocks and carbon sequestration.

With a focus on the Queensland Brigalow Belt, researchers looked at the shared effects of soil carbon and nitrogen in relation to productivity and land management achieved by managed native forest regrowth.

Properties sharing similar soil and vegetation, but managed differently, were sampled for soil carbon. Statistical and carbon turnover models – including RothC – explored how climate and management at these properties interacted to influence the rate of carbon turnover.

Initial models suggested that management effects on soil carbon depend on local climate and variation in soil type. Factors such as air temperature, soil phosphorus and use of fire during Brigalow development had strong effects on soil carbon stocks and turnover.

Both carbon models suggested losses in soil organic carbon stock since conversion of remnant Brigalow land to other land uses.

Further examination of historic methods of clearing will build a clearer picture of how soil carbon stocks change under various management methods.

Coupling carbon models with remote-sensing information could give researchers a richer picture of useful measures, such as changes in tree canopy density over time.

Implications

The findings have particular relevance for anyone involved in the management of lands previously under remnant vegetation, including facilitated native forest regrowth and/or grazing lands.

This group includes graziers and pasture croppers, governments at all levels, NGOs (e.g. catchment associations, community groups and environment trusts) and private industry (commercial offset businesses).



Researchers taking a collection of soil cores for measurement of soil carbon stocks in Brigalow regrowth, Queensland.

Research separating the different effects of climate and management is used to inform policy makers, industry and individuals, including cost-benefit and scenario analysis for balancing productivity and management of native forest regrowth.



Significance of the findings for Australian agriculture

Models suggest the clearing of Brigalow and its replacement with pasture reduced soil organic carbon stocks by five tonnes per hectare at the minimum, up to more than 12 tonnes per hectare on moderately alkaline soil.

Separating the effects of climate and management, including interactive management effects and legacy effects of prior land use, requires detailed accounting for grazing interaction and remains a significant challenge for this research. Even though there is regrowth in these sites, the way in which grazing occurs changes with the regrowth stages as well as the land type of interest.

Research impact for policy, industry, individuals

Farming practices likely to be affected by this research include grazing and forest management (grazing type, grazing intensity, location and duration; fencing of land types and land use; investment required to maintain productivity balance between pasture and regrowth; method of regrowth management; and fire management).

For policymakers, there is now quantified soil organic carbon information that can inform ERF determinations, in particular, different ways to compare the directly measured and modelled estimations within a 25-year time frame, which is the current determination for the managed native regrowth, as well as through a 100-year time frame.

Industry groups are likely to be affected by these determinations through selection of land suitable for the activity, cost-benefit analysis of managing regrowth, grazing and its interaction over time, and the likelihood of policy uptake by individuals and/or aggregator groups.

Storage of the samples collected as part of this research in a national soil archive provides a valuable resource to support ongoing research and extension efforts. In the future, as new technologies and methods are developed, a physical sample for reference will be available for comparison over time.

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Environmental plantings

The *Environmental plantings* project aimed to improve the accuracy of predictions of soil carbon sequestration after reforestation, and enhance FullCAM-based ERF methodologies that include environmental plantings. This would allow Australian farmers who are integrating reforestation activities into their farms to fully benefit from carbon credits, not just in tree biomass and litter (as in current ERF methods available for environmental plantings), but also in the soil.

Extensive collaboration allowed researchers to sample above and belowground biomass and soil carbon at more than 120 sites across a wide range of geo-climatic regions. The results gave sound relationships to improve both the methodologies and calibrations of the FullCAM model for biomass, and rates of litterfall and decomposition.

Average carbon sequestration within biomass, litter and soil of relatively young environmental plantings ranged between two and 10 tonnes of carbon per hectare. Although most sequestration is in biomass, soil carbon contributed, on average, eight per cent of that sequestered, and was particularly high in ex-cropping sites.

In addition to improved understanding of soil carbon sequestration following reforestation, the study found that FullCAM significantly underestimated carbon sequestration in biomass of environmental plantings. This was particularly prevalent in the belowground or



Researcher at one of the 120 paired environmental planting and adjacent agricultural sites where carbon in biomass, litter and soil were studied.

root components of these plantings, and in plantations established in riparian zones for erosion control or water quality improvement.

Implications

Australian agriculture and policymakers

FullCAM currently underestimates carbon sequestration in environmental plantings in some situations, and this project improved calibrations. As a result, predictions of carbon sequestration by environmental plantings will increase in many situations, particularly in riparian zones. This is due in large part to increase estimates in biomass in the roots of these plantings.

While changes in predicted carbon sequestration from soil carbon following reforestation are small compared with the biomass and litter, this additional fraction can now be accurately predicted and included in methodologies.

These enhancements to FullCAM, if included by regulators into ERF methods, mean that

farmers could increase income from their participation in carbon markets, while also contributing to landscape remediation, providing biodiversity benefits and delivering benefits to agricultural production and sustainability.

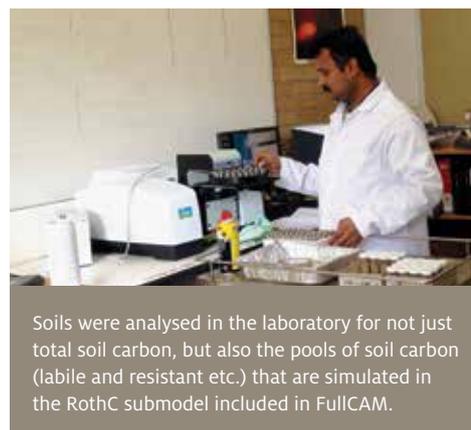
Facilitating ERF methodology development

The project showed that current FullCAM predictions of soil carbon (and root biomass) following reforestation were sometimes inaccurate. Preliminary calibrations have improved the accuracy of the predicted carbon sequestered. ERF methodologies for woody systems (e.g. environmental plantings, regrowth, natural regeneration, farm forestry) are currently being combined into a new single method using FullCAM.

Despite the capacity of FullCAM to predict soil carbon, this pool is not included in this method. Using the FtRG-data, the potential exists to include this fraction and to validate initial calibrations against a wider range of woody systems and geo-climatic conditions. With accurate FullCAM predictions of all pools of soil carbon using *Filling the Research Gap* (FtRG) data, a new ERF method can be created with higher carbon sequestration than those that do not include soil carbon.



Researchers marking out plots for soil carbon sampling at one of the 120 paired environmental planting and adjacent agricultural sites where carbon in biomass, litter and soil were studied.



Soils were analysed in the laboratory for not just total soil carbon, but also the pools of soil carbon (labile and resistant etc.) that are simulated in the RothC submodel included in FullCAM.

Increasing productivity and sustainable land use

Environmental plantings can be used by farmers as riparian plantings, in alley crop configurations to decrease soil erosion, and to manage the farm's water availability and mitigation of salinity. Similarly, the shelter that environmental plantings can provide for stock may also provide longer-term sustainability of grazing enterprises under climate change.

Improvements to the accuracy of the FullCAM model as a result of this project will increase the economic appeal of establishing these belts. Farmers establishing shelterbelts of environmental plantings could obtain a win-win: increasing production while also receiving an increased carbon payment.

Through this work, farmers are better able to use environmental plantings as tools to manage their longer-term sustainability, given the costs of establishment of these planting may be partially offset through carbon payments.

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Soil carbon benefits through reforestation

The *Soil carbon benefits through reforestation* project aimed to determine the soil and biomass carbon change from reforestation across hardwood and softwood, savannah and rainforest ecosystems in subtropical and tropical Australia. Researchers compared pasture with reforested areas – as well as including three-way comparisons with remnant native vegetation areas – to quantify changes in soil carbon with land use.

They found that soil carbon levels had declined with remnant native vegetation to pasture land use changes, and that cultivation

caused further declines. Reversing soil carbon decline through reforestation is a slow process; it typically takes more than 15 years for the soil carbon levels to exceed that of pasture.

Younger reforested areas had similar soil carbon levels to pastures, but older plantations had increased soil carbon (especially when tree roots biomass was included) beyond that achieved with pastures.

Substantially more carbon is stored in aboveground biomass with tree plantings, compared with pasture or cultivated land uses. Therefore, reforestation is a viable option for maintaining or restoring soil carbon over the longer term and is an excellent management option for Australian agriculture, particularly in degraded land.

A case study based on a mixed species rainforest planting in northern Queensland showed that there have been significant losses of carbon associated with conversion of remnant rainforest to pasture. However, a change of land use from grazed pasture to a young rainforest plantation restored 21 per cent (+59t/ha) of the total lost carbon stock (122t/ha to 181t/ha) at an average yearly gain of approximately 8.4t/ha/year. While there was little change in soil carbon between land uses, there was an increase in belowground carbon due to the contribution of tree roots. Further analysis of the mixed rainforest species sites in north Queensland is needed to determine if there are changes in soil carbon as planting age increases.



Forest ecologist Tom Lewis soil sampling in the north Queensland rainforest.



Jenny Sinclair from Green Collar Group collaborated with the Reforestation group to refine soil carbon determination methods using NIR spectroscopy.

Revegetation with tree plantations can increase carbon storage in the landscape through carbon in tree biomass, debris biomass and through modest increases in soil carbon. Sequestration of soil carbon associated with tree plantings could provide landholders with an additional source of income through carbon credit schemes.

In addition to the aims of quantifying the changes in soil carbon, the project involved an economic analysis of the profitability of reforestation projects (see page 14).

The species examined included African mahogany, spotted gum, building material timbers such as pine, and mixed-species environmental plants.

Soil sampling techniques for reforestation were also refined as part of the project. Mounding and other disturbances created a great deal of variability on the sites where researchers were sampling soil organic carbon levels. They determined that a minimum of eight plots of 10 bulked soil cores were required to minimise sampling error in variable reforestation sites. 'Wetting-up' techniques were also required for dry kandosol sites in the Northern Territory.

Implications

Farming/land management practices and soil carbon policy

The project has filled some large knowledge gaps related to soil carbon associated with tree-based systems in northern Australia. These findings provide confidence to policymakers, industry groups and farmers that trees in the landscape can rebuild carbon stocks where they have previously been depleted.

The economic analysis of farm forestry plantings showed borderline returns for growing hardwood species for the building industry, although high-value species such as African mahogany were likely to provide economic returns to the grower. Additional income through carbon credits or alternative sources (such as tourism, as found in north Queensland) was required to provide viable returns for hardwood plantations and amenity plantings. The analysis concluded there is unlikely to be a significant land use change to carbon forestry based on current carbon prices.

Other drivers for reforestation include rehabilitation of degraded land, windbreaks for crops, livestock shelterbelts, buffer zones for watercourses and wildlife corridors.

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Economic analysis: carbon benefits through reforestation

As part of the broader project investigating soil carbon benefits through reforestation, an economic analysis was conducted on the three contrasting farm forestry systems: spotted gum in south-east Queensland, African mahogany in the Northern Territory, and mixed rainforest species plantings in North Queensland. This financial viability analysis was intended to inform the decision-making process of landholders who may be interested in reforesting some of their land, as well as to demonstrate the potential of crediting carbon in both the soil and biomass of a forest, for which there is currently no ERF method.

For the purpose of the analysis, it was assumed that Australian Carbon Credit Units (ACCUs) would be paid for one 25-year crediting period as outlined for sequestration projects under the ERF (at the time of analysis). The permanence period was assumed to be 100 years, meaning that the project must be run over that time and there must be no net loss in soil or biomass carbon over the project life.

For each site, the net present value (NPV) of the costs and benefits was identified using the best guess estimates including a discount rate of 8.7 per cent. The key parameters (including general and site-specific assumptions) are outlined in Table 1. To test the sensitivity of the resulting NPV to some key parameters, a sensitivity analysis was undertaken separately on five parameters at each site, with each

parameter set at low and/or high levels, holding all other parameters at the medium (best guess) level. The low carbon price was set to zero to test for the scenario that there is no value of carbon, and the high value (originally \$24) is the fixed price of carbon under the previous legislation.

Prices of both carbon and timber have the potential to fluctuate greatly over time, so in addition to a sensitivity analysis, a risk analysis was conducted to simulate the annual variability of these parameters over the life of the project (up to 100 years). The results of the risk analysis demonstrated that at a discount rate of 8.7 per cent, stumpage price (the price paid for the right to harvest timber) caused the NPV to vary quite substantially from year to year, while carbon price had relatively little influence.

The results of the sensitivity analysis demonstrate that irrespective of which parameters are changed, the NPV of the African mahogany site remains positive, while the NPV of the Mixed environmental site remains negative (Table 2). For the spotted gum, the discount rate and final harvest stumpage price appear to have the largest impact on the NPV, resulting in positive NPVs. The carbon price has a less substantial influence, but results in a positive NPV with a carbon price of \$24.15.

In the current scenario, the financial viability of carbon forestry in commercial plantations is influenced less by the price of carbon and more by the value of the harvestable timber. Previous studies found significant variation in economic viability between case studies, with some sites even yielding a positive NPV despite a carbon price of zero, due to the value of the timber.

Table 1: Key parameters used in the cost-benefit analysis

<i>a. General assumptions</i>	<i>Value</i>		
Permanence period (years)	100		
Reporting frequency (years)	5		
ACCUs sold (% of total)	100		
Timber sold (% of total stumps)	100		
All non-trunk AGB (branches and leaves) left on site (% of total tree)	55		
Harvest age (years)	25		
Establishment management (\$/ha)	100		
Carbon credit processing (\$/t CO ₂)	1		
Auditing cost (\$/audit report/ha)	10		
Soil sampling cost (\$/ha)	0		
Carbon price (\$/ACCU)	5.35		
<i>b. Site specific assumptions</i>	<i>African mahogany</i>	<i>Spotted gum</i>	<i>Mixed environmental</i>
Opportunity cost of land (\$/ha)	781.8	781.8	0
Establishment costs (\$/ha)	1,821.37	2,560.60	6,508.28
Ongoing costs (\$/ha)	1,814.53	2321.6	0
Plantation density (trees/ha)	1,000	1,000	2,500
Plantation biomass (determined using)	Allometric equation	FullCAM model	FullCAM model
Soil carbon sequestration (t/ha/yr)	0.96	N/A	0.57
Final harvest timber price (\$/m ³)	494.26	62.33	
Commercial thin timber price (\$/m ³)	247.13	58.18	N/A

Table 2: Results for sensitivity analysis (NPV)

	<i>African mahogany</i>	<i>Spotted gum</i>	<i>Mixed environmental</i>	
<i>Discount rate (%)</i>				
Low	\$53,364	\$1,290	-\$5,736	
Medium	\$36,392	-\$1,443	-\$5,722	
High	\$27,466	-\$2,846	-\$5,701	
<i>Carbon Price (\$/t CO₂)</i>				
Low	\$36,202	-\$1,983	-\$6,161	
Medium	\$36,392	-\$1,443	-\$5,722	
High	\$37,233	\$452	-\$4,183	
<i>Stumpage (\$/m³)</i>				
Commercial thin	Low	\$18,396	-\$3,482	N/A
	Medium	\$36,392	-\$1,443	N/A
	High	\$41,218	-\$410	N/A
Final harvest	Low	\$16,290	-\$4,045	N/A
	Medium	\$36,392	-\$1,443	N/A
	High	\$41,286	\$1,182	N/A
<i>Soil Sampling Cost (\$/m²)</i>				
Medium	\$36,392	N/A	-\$5,722	
High	\$34,726	N/A	-\$7,388	

* Carbon price set to \$0 for low, \$5.35 for medium and \$24.15 for high

The results of this financial viability study demonstrate that additional income through carbon credits or alternative sources (such as tourism as found in North Queensland) is required to provide viable returns for hardwood plantations and amenity plantings. High value species such as African mahogany were likely to provide economic returns to the grower. Based on the current carbon

prices and substantial costs, significant land use change to carbon forestry is unlikely. However there may be financially viable options in other similar ventures without large establishment costs, such as through natural regeneration of forested areas.

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EverCrop Carbon Plus

Discussion

EverCrop Carbon Plus was a collaborative project that examined the deep soil carbon sequestration potential of perennial species in cropping soils. Cropping environments are typically dominated by annual species such as wheat. A shift to a perennial-based system – with an increased ability to use rainfall and greater belowground allocation of carbon associated with root mass – was suggested as a way to increase soil organic carbon in agricultural landscapes.

Comparisons included the most feasible perennial plant options used in a range of environments, including the northern Western Australian wheatbelt, the South Australian Mallee, and the medium-rainfall cropping zone of south-eastern Australia. Forage shrub species, tagasaste and saltbush, tropical perennial grasses, and a small range of temperate herbaceous perennial species including lucerne made up the species examined.

Researchers focused on soil depths beyond the IPCC standard of 0.3 metres. This took into account the deeper root systems of perennial plants and the likely greater permanence of carbon in root material in those layers of the soil profile less likely to decompose. Additionally, decomposition rates of herbaceous perennials were quantified with the aim to identify mechanisms



Soil sampling to a depth of four metres under perennial grass pasture at Moora, WA.

for C-sequestration in deep-rooted perennial systems.

Findings

- Tagasaste, and to a lesser extent saltbush, showed potential to sequester significant quantities of carbon. There was almost double the amount of soil organic carbon under the dense (2300 trees/hectare) tagasaste planting compared with the annual control. The total carbon sequestration rate (biomass and soil) was estimated at 9.2 tonnes CO₂-e (CO₂ equivalents) /ha/year, for the 22-year lifespan of the trial site. Importantly, tagasaste was established on soils that were known for poor productivity under conventional agriculture.

- There were no significant differences in soil organic carbon stores in the surface two metres under grazed saltbush plantings compared with annual plantings. However, there was a sequestration rate estimated to be between 0.7 and 2.3 tonnes CO₂-e/ha/year in biomass. While less than tagasaste, it still represents a significant potential, particularly when associated agricultural production benefits are included and the fact that saltbush can be grown on land that has low productivity for agriculture.
- Economic analysis, which included the impact of carbon sequestration, showed that tagasaste could be a viable component of farming systems, particularly on soils of low fertility (see page 18).
- Herbaceous perennials were ineffective in sequestering soil carbon, largely due to fast breakdown of the plant residues.
- The development of a protocol for identifying C-contamination in soil samples attributable to coring tube lubricants increases our confidence in using archived soil samples, where they exist, to establish benchmarks to account for changes in soil organic carbon.



Examining decomposition rates of plant roots deep in the soil profile at Wagga Wagga, NSW

Implications

Australian agriculture and policymakers

Sustainable land use

If carbon was an additional economic incentive, using shrubs to manage degraded landscapes such as deep infertile sands and salt-affected land would be more likely. There are few other instances of increased carbon stocks in soil as a result of the inclusion of perennial species (relative to annual species). Perennial pastures play an important role in mixed crop/livestock systems, valued for grazing, stabilising production particularly in drier or more variable climates, reducing soil erosion, reducing groundwater recharge and for benefits to soil biological functioning. However, the results indicate that in the short term increasing carbon stocks, even when soil below 0.3 metres is considered, will not be a strong driver for their adoption by farmers.

Implications for farmers

The highest potential for sequestering carbon was found in the long-term tagasaste plantation. Other shrub options such as saltbush may offer opportunities to sequester carbon, mainly in biomass rather than in soil. Perennial pasture options are less effective for sequestering carbon due in part to their faster decomposition rates. Most soil organic carbon was found in the surface 0.3 metres and little evidence was found in any perennial system to justify sampling to below this depth to account for changes in soil carbon stocks.

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Economic analysis - tagasaste

Tagasaste shows the potential to sequester substantial amounts of carbon. The researchers investigated the economics of including emissions abatement as a new enterprise within systems where tagasaste is grown on deep sands and grazed by cattle. The purpose of this was to compare tagasaste-based enterprises with the existing annual pasture systems common in the areas suited to tagasaste.

Four scenarios were modeled.

1. A **Block** scenario models dense tagasaste rows at seven-metre intervals, with a carrying capacity of 10 Dry Sheep Equivalent per hectare (DSE/ha).
2. A **Wide Alley** scenario models less dense tagasaste alleys at 30m intervals, with a calculated carrying capacity of 5.95 DSE/ha.
3. A (default) **Annual** scenario assumes that low-cost annual pastures are grazed. Due to poor soils, this scenario provides a low carrying capacity of 3.25 DSE/ha.
4. An **Unmanaged** scenario models an ungrazed, dense tagasaste plantation used only for carbon sequestration.

To conduct the analysis three models were developed:

- a cattle enterprise model
- an emissions model
- a sequestration model.

The models fed into a discounted cash flow (DCF) where the net present value (NPV) for each scenario was calculated to compare scenarios.

Figure 1 illustrates the NPV results from the modelling with default parameters. The NPV from the abatement enterprise includes only the costs and income that are not part of the cattle enterprise.

The positive NPVs from the abatement enterprise are sufficient to pay the establishment costs.

The **Block** scenario represented the best economic proposition with its NPV being in excess of \$2000/ha more than the NPV attained under the **Annual** scenario.

Figure 1: NPV results for the four scenarios under default parameters.

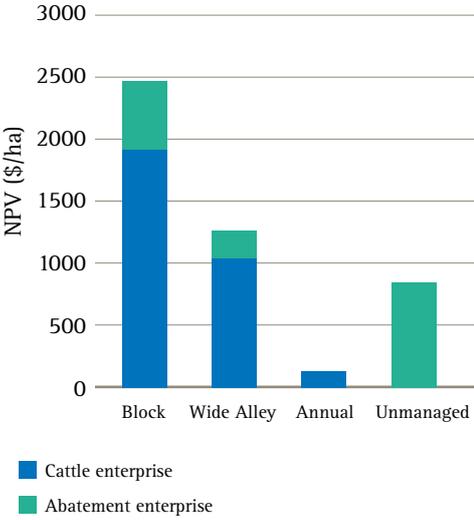
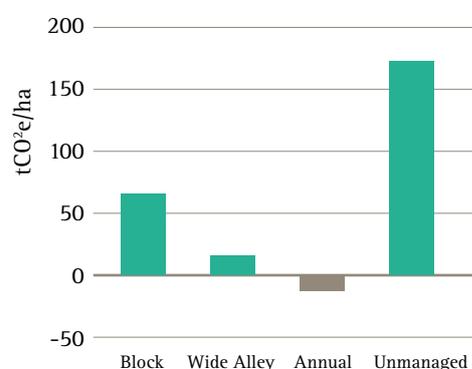


Figure 2 illustrates the total abatement from each scenario over the lifetime of the project. The significantly greater emissions abatement achieved under the unmanaged stand is explained by increased carbon sequestration in soil and herbage under the ungrazed plantation and no methane emissions associated with grazing livestock.

Figure 2: Total Abatement achieved by each scenario over the project lifetime. Note that the Annual scenario can be used as a baseline to calculate net abatement.



To calculate the net abatement, the **Annual** scenario was treated as the emissions baseline for the other scenarios. The Annual scenario was modelled to have a slightly negative emissions value, reflecting minimal C-sequestration and some methane emissions from a low stocking rate of grazing livestock. Therefore the net abatement was even greater for the tagasaste treatments than depicted in Figure 2, and the **Block** scenario still achieves more than twice the net emissions abatement of the **Wide Alley** scenario. While the **Unmanaged** scenario abates the most carbon dioxide, the **Block** scenario manages to achieve 43 per cent of the **Unmanaged** net abatement while tripling the **Unmanaged** NPV.

Conclusion

The study showed that receiving payments for emissions abatement improved the financial viability of tagasaste plantations for existing cattle-grazing enterprises and provided a new option for farmers without livestock to derive an income from tagasaste. A sensitivity analysis on the carbon price found that if the carbon price was above \$9, both the **Block** and **Wide Alley** scenarios would receive enough abatement income to pay for the upfront establishment costs of the tagasaste, under the discount rate regimes considered (up to 10 per cent). Obviously, the higher the carbon price is, the more financially appealing ungrazed tagasaste will be for farmers. Tagasaste is commonly grown on deep sands in southern Australia where its large root system can explore the soil volume and access water at depths well below the rooting zone of other agricultural plants. Tagasaste can therefore thrive on soils that are marginal for annual crop and pasture production. If farmers on such landscapes could realise an additional income from emissions abatement by planting their marginal cropping land to a shrub like tagasaste, it will not only be of financial benefit to them as the economic analysis suggest, but it will also likely lead to better environmental outcomes on more marginal soil types. Given the impressive results from the **Block** scenario, the increased productivity, and the exciting potential for carbon sequestration and abatement income, further research into tagasaste sequestration is warranted.

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Soil

Amendments

Compost and biochar

The *Compost and biochar* project sought to assess the feasibility of using organic amendments on tropical agricultural systems, in particular on the use of co-composted biochar (biochar composted with organic matter). Researchers were aiming to learn how these organic amendments would affect carbon sequestration, soil nutrient content and greenhouse gas emissions reductions in tropical soils.

Seven field trials in North Queensland were established on sugarcane (x2), banana (x2), maize (x1), peanut (x1) and papaya (x1) farms.

Key findings

- Soil carbon – all amendments containing biochar increased soil carbon, with little evidence of an increase in soil carbon due to compost, except where native carbon stocks were lowest.
- Soil water content – soil water content was significantly improved at most sites under most organic amendments.
- Soil condition – clay-rich soils showed significant improvement in soil nutrient status. Improvements in soil nitrogen, phosphorus, pH, exchangeable cations and soil bulk density were all recorded.
- Soil resilience – both the short and long-term application of biochar/compost can improve the resilience of soils, including greater retention of nutrients and



Biochar is the highly stable carbon-rich product of the high-temperature heating of biomass in the absence of oxygen. It is similar to charcoal, but is produced with the specific purpose of carbon sequestration and as an agricultural amendment. Compost (partly decomposed organic residues) has been used to improve soil fertility for thousands of years.

improving resilience to drought.

- Crop yield – yields improved by up to 30 per cent on clay-rich, basalt-derived soils. There is the potential for further improvement over time.
- Plant performance – the organic amendments had comparatively little impact on leaf chemistry at any site. Where positive effects were identified, these tended to occur at sites where parallel improvements in soil condition were noted.
- Greenhouse gas emissions – CO₂ emissions were elevated in organic-amended treatments due to the additional source of easily decomposable carbon in compost. However, this initial pulse lasted for four to six weeks and was offset by long-term carbon sequestration in biochar-containing treatments. All organic amendments

reduced total N₂O emissions. The highest reductions were seen in the biochar-only treatments.

Biochar and compost production are niche industries in North Queensland and the costs of production are the major barrier to implementation on-farm. However, 'industrialisation' of biochar production and broader uptake would substantially drive down the price. Recent work has suggested that biochar will become a more attractive option in the future.

Implications

There are public-good benefits from the adoption of organic amendments by farmers that are not reflected in immediate on-farm economic considerations. These include: the potential to provide a more sustainable and cost-effective avenue for the reuse of industrial and municipal nutrient and/or carbon-rich waste streams; and the potential to reduce nutrient run-off to local waterways and to the Great Barrier Reef – one of the most significant threats to the environment in northern Queensland.

There is, therefore, potential for the adoption of farming practices involving the use of compost and/or biochar in combination with other management actions, but these are not yet cost competitive.

To make inroads into changing management practices on farm, it will be necessary to demonstrate the economic and environmental benefits from the use of organic amendments over the longer term, in combination with other management options such as reduced tillage. If such benefits can be demonstrated, policy settings could be implemented to offset the cost of adoption in the shorter term, in recognition of the longer-term on-farm benefits and broader environmental and social benefits.

On-farm benefits include yield improvement, improved water and nutrient use efficiency, improved soil and crop resilience in a climate characterised by significant, and potentially increasing, variability in rainfall. Broader environmental and social benefits include carbon sequestration, reduced nutrient run-off, reduced greenhouse gas emissions, and reuse of nutrient and/or carbon-rich municipal and industrial waste streams.

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Acacia biochar being blended with municipal green waste and chicken manure at the King Brown Technologies compost production facility in Mareeba on the Atherton Tablelands, North Queensland.

Carbon sequestration potential of organic soil amendments

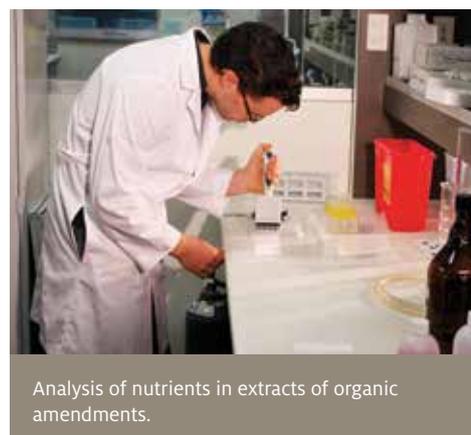
The *Carbon sequestration potential of organic soil amendments* project facilitated the collection and analysis of data from more than 120 organic amendments over five categories.

The aims of the project were to:

- construct a database of these organic amendments
- characterise them chemically using a range of techniques
- quantify their stability
- quantify the effects of soil types on the stability of the organic amendments
- model CO₂ release from stability experiments and relate this to chemical characterisation.

The organic amendments were incubated for 18 months in a sand matrix with a small amount of microbial inoculum sourced from 200 diverse Australian agricultural soils. This allowed researchers to assess the biological and chemical stability of the organic amendments by measuring their decomposition and CO₂ production.

Modelling of these emissions allowed researchers to partition organic amendment carbon into fast and slow-cycling pools, which are comparable to decomposable particulate matter (DPM) and resistant particulate matter (RPM) in a RothC or FullCAM modelling framework. Further, using both the specialised nuclear magnetic resonance (NMR) spectroscopy and also more accessible mid infra-red (MIR) and near infra-red (NIR) techniques, these pools could be related back to the chemistry of the organic matter in the starting organic amendments.



Analysis of nutrients in extracts of organic amendments.

Key findings

- Composts, biosolids, manures and plant residues form a continuum of stabilities, with biochars separate.
- Policy should consider a unified approach to accounting for carbon from organic amendments.
- The project identified which chemical properties drive stable or labile behaviour in organic amendments.
- NMR and rapid spectral techniques show

promise for accurate prediction of the partitioning of organic amendment carbon, but not of the turnover rate.

- There is potential to develop predictive capacity to estimate partitioning of organic amendment carbon to 'less-stable, DPM' and 'more-stable, RPM' pools.
- Turnover rate of 'RPM-like' pool is linked strongly to soil properties.
- Models such as RothC and/or FullCAM may successfully predict the fate of organic amendment carbon upon application to soil if partitioning to RPM and DPM is matched to chemistry.

Implications

Significance of findings for Australian agriculture and associated industries

There is much interest in the application of organic amendments to agricultural soils not only as a potential carbon sequestration mechanism, but also to improve soil health, nutrient cycling, provision of ecosystem services, increase water-holding capacity and moisture storage, and to ultimately maintain or increase sustainable agricultural production.



Nuclear magnetic resonance (NMR) spectrometer for the analysis of organic amendment carbon chemistry.

This work provides landholders and agronomists with an extra tool with which to assess how stable an organic amendment may be upon application to the soil. From a waste-management perspective, the application of organic 'wastes' and their products to land, especially when soil quality or production may be improved, is considered preferable to landfill or stockpiling.

Impact for policymakers

In terms of agricultural greenhouse gas abatement, the significant variation in the chemistry and stability of carbon in organic amendments raises questions as to how policies relating to the use of organic amendments to sequester carbon in soils can be conceived and applied. Policy-makers could encourage those who use waste resources in their products to provide information on the stability of the carbon within their products. This will allow users of these products to make informed decisions in regards to potential longevity of the carbon in the organic amendments that they apply.

Impact for farmers

The ability to predict the stability of organic amendments is of direct benefit to farmers, as it would allow them to screen before making a decision based upon their stability. While the stability of the carbon in organic amendments is of interest to farmers from a carbon-sequestration and potential greenhouse-gas-mitigation perspective, it also provides an idea of how rapidly nutrients contained within organic amendments may be released. This would allow farmers to better manage their fertiliser requirements after application of organic amendments, which would potentially have an impact on nitrogen use efficiency and direct fertiliser costs.

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Improved
Measurement



Quantifying temporal variability

The *Quantifying temporal variability project* looked at whether changes in soil carbon stocks were the result of altered management practices or if other factors could produce a change in soil carbon measures.

The aim was to make recommendations on how soil should be sampled to optimise the detection of temporal changes and to quantify the temporal variation in soil carbon stocks.

In addition to the potential implications of changes in management, researchers found measured differences in soil carbon stocks could arise due to:

- temporal differences in the addition of organic carbon to soil. These result from seasonal variations in plant growth rates and the timing of agricultural management practices.
- variations in the methods of collecting soil samples. Minor variations in the depth of the sample and measures such as soil water content can influence the mass and density of the sample
- spatial variation in soil carbon content and bulk density that may exist within the measurement area.
- variation arising from preparation and analytical techniques.

By using equivalent soil mass figures, researchers were able to remove most of the variation that could be attributed to differences in sampling as well as some of the

spatial issues related to variations in soil properties other than carbon content (e.g. bulk density).

Findings

Stocks of soil carbon and its component fractions were measured monthly for two years. This data has clarified some requirements for soil carbon accounting projects.

- Collecting composite soil samples at multiple times can reduce the impact that spatial variability has on calculations of soil carbon stocks and provide an improved ability to detect true underlying temporal trends.
- All calculations should be completed using an equivalent soil mass approach to remove the effects of variations in bulk density and any variations in the sample collection methods.

Implications

Significance of findings for Australian agriculture

The findings of this project will continue to guide the development of measurement-based soil sampling schemes for the purpose of carbon accounting. Having these schemes in place will ensure that appropriate decisions are made with regard to the management activities that can promote carbon accumulation in soil or avoid emissions.

Impact on policymakers, industry groups and farmers

The research will help instruct policymakers, industry groups and farmers on how to optimally collect soil samples.

Prior to this project, it was difficult to understand the basis upon which people were claiming to have sequestered 10 tonnes of carbon per hectare per year in their soils. This project has shown that monthly measurements of soil carbon stocks can differ by -11.4 tonnes to +11.4 tonnes due to spatial variation. As more measurements of carbon stock are taken over time, a better estimate of the true temporal trend can emerge. Farmers, industry groups and policymakers need to be aware that basing carbon accounting payments on only a few temporal measurements could produce results that do not reflect the true trend.

CFI/ERF methodology development

The direct measurement CFI soil carbon methodology employs a sampling scheme based on the use of composite samples that captures the spatial variability within measurement areas equally. Given the fluctuations in soil carbon stocks noted between monthly sampling events, the CFI

methodology was constructed to require multiple measurements and employ a regression approach to quantifying temporal change. Under such an approach, as the number of soil sampling events increases it is more likely that the true temporal trend will emerge from the noise created by spatial variability. Without this approach, the potential for obtaining false trends and either over or under-crediting landowners remains high.

Sustainable land use

By improving our understanding of how land use and agricultural management practices affect soil carbon stocks, options to help landowners build these stocks will be able to be identified.

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Analysis of soils by mid-infrared spectroscopy to predict the contents of organic carbon and its composition (allocation to particulate, humus and resistant fractions).



Improved measurement and understanding of soil carbon and its fractions

Cost-effective ways to measure and monitor soil organic carbon stocks are needed to assess land management practices that aim to capture and retain soil organic carbon (carbon farming).

Traditional sampling and measurement methods are expensive compared to the value of the stored organic carbon. They also do not give the information on soil organic carbon fractions required by models such as RothC, or those incorporating RothC, that are used to predict changes in organic carbon stocks.

The *Improved measurement and understanding of soil carbon and its fractions* project focused on developing techniques to rapidly and routinely measure numerous soil properties at a lower cost. This research was a one-year, proof-of-concept study to assess the ability of visible and near infra-red spectroscopy to measure soil carbon fractions.

Vis/NIR spectroscopy represents a more 'on-the-go' technology than mid infra-red (MIR). There is less sample processing and no need to grind the samples, they are less sensitive to moisture and there are field-portable instruments readily available.

Vis/NIR spectroscopy works well for measuring total soil organic carbon, so researchers were keen to see whether it could also be used to predict carbon fractions.

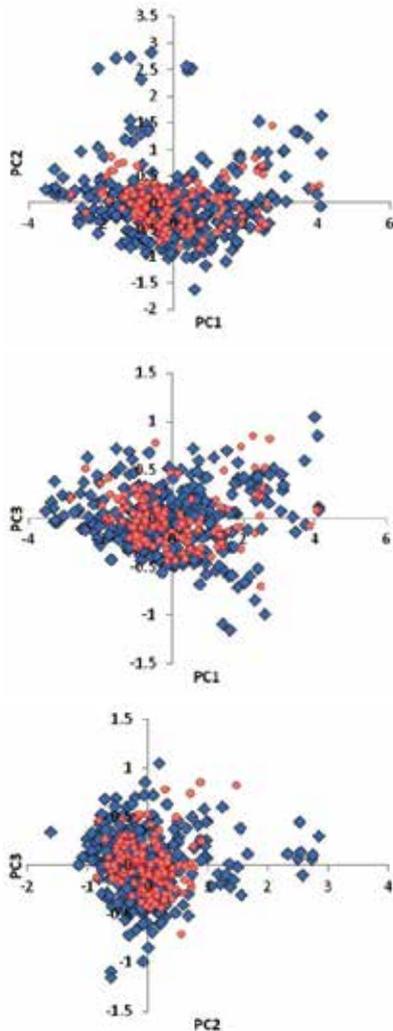
Methods

The soil samples originated from National Soil Carbon Research Program (SCaRP) projects. The farm paddock sample sites met specific combinations of agricultural management by soil type and there was a random selection of sampling locations from an identified soil type.

A key objective of SCaRP was consistent sampling, processing and analysis to enable a consistent national soil carbon database to be developed. At each sampling site, a total of 10 samples were collected from a 25m x 25m area. Soils were sampled in 0.10 metre increments to a depth of 0.30 metres. The 10 samples collected for each depth were either composited (at 95 per cent of sampling sites) or kept separate (at 5 per cent of sampling sites) for all subsequent processing and analyses.

Samples were kept separate to examine the extent of variation within the sampling site and to provide the data required for future sampling activities to assess the magnitude and standard deviation associated with soil carbon change. All collected samples were air dried, sieved to <2000 µm and well mixed.

Soil C fraction datasets



Bivariate plots of the first three principal components of the calibration (diamonds) and verification (circles) spectral data sets.

The project used two sets of fully characterised soil samples.

1. A calibration set consisting of 309 non-calcareous soils that form the basis of the MIR-PLSR regressions and used by all SCaRP projects.

2. A verification set consisting of 133 additional non-calcareous samples selected out of the SCaRP soil archives.

Key findings

An Australian soil carbon library of vis-NIR spectra was established using samples and analytical data from SCaRP. This measured variations in SOC stocks and composition under different agricultural management practices in important Australian agricultural regions. The researchers limited the analyses to non-calcareous soils.

This research has demonstrated that vis-NIR spectroscopy is a viable alternative to MIR spectroscopy for predicting soil organic carbon content and its distribution into major organic carbon fractions. Calibration and verification statistics were not quite as robust as those found when using MIR spectroscopy but the significantly reduced amount of sample processing needed to acquire vis-NIR spectra can outweigh this small loss of certainty in predictions depending on the application.

This research represents an intermediate step in making vis-NIR spectroscopy a truly 'on-the-go' technology for soil carbon research. The next step will be to see how the models perform when soil samples are measured in the field.

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Soil carbon by spectrophotometry

A method for efficient and accurate project-level soil organic carbon determination using *in situ* spectrophotometry and advanced spatial analysis

Sequestration of carbon in soil has significant potential for climate change mitigation and adaptation needs, with soil containing more carbon than the vegetation and atmospheric pools combined. However, soil organic carbon content is susceptible to land management approaches.

Land management methods to improve soil organic carbon stocks are well understood, as is the ability to measure carbon content in individual plots. However, a significant research gap existed, as the techniques and methods for analysing individual soil samples to determine project-level soil organic carbon stocks yielded inaccurate results.

The current methods of deriving soil organic carbon stock are time-consuming, labour intensive and costly. They rely on excessive and repetitive sample collection and subsequent off-site lab analysis to derive soil organic carbon stock.

The *Soil carbon by spectrophotometry* project aimed to demonstrate a commercially cost-efficient method to measure rangeland soil organic carbon content and composition for application in the CFI/ERF methodologies, using satellite data and field-based

spectrometry. The project covered 65,000 hectares of central Australian rangeland across two properties, 'Utopia' and 'Beetaloo'. The goal was to further improve sampling efficiency and confidence in soil organic carbon estimates.

Key findings

Although soil organic carbon was relatively low at Utopia (which is typical of sandy soils) and at Beetaloo (due to the presence of clays and gravels), there was a relationship between soil organic carbon content and reflectance of the soil in the vis-NIR (visible near infra-red) spectral range.



Spectral sampling using a mounted Veris VIS-NIR spectrophotometer with hydraulic probe.



Utopia is an Aboriginal Homeland located in central Australia. The property is approximately 360,000ha characterised by lateritic sandy soils and undulating dunes.

Soil organic carbon varies by depth; subtle differences in mean vis-NIR spectra from soil samples collected at different depths were observed. Researchers were able to demonstrate the capacity to use *in situ* vis-NIR spectra combined with satellite data to calibrate a model for prediction of soil organic carbon with reasonable accuracy.

The generation of spatial map data of the percentage of soil organic carbon for each study area gave a promising outlook for the application of remote sensing data as a proxy for soil carbon.

Implications

This project delivered a way to determine soil organic carbon stocks over a large area. Accurate soil organic carbon assessment is crucial for determining the abatement generated by altered land management practices in the Australian rangelands.

Furthermore, the method determines soil organic carbon stocks independent of land

management practices. This allows for the inclusion of the soil organic carbon pool in a broad range of methodologies.

The outcome of the project is a more accessible sampling regime that is cost and time efficient. This has the potential to reduce the financial and logistical barriers for adoption of environmental schemes such as those funded by the CFI/ERF.

The project also generated a series of reports and technical documents that provide the level of certainty demanded by the CFI/ERF and the Emissions Reduction Assurance Committee (formerly the Domestic Offsets Integrity Committee) for approval of projects.

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Management
Practices

Maintenance of SOC in grain production

The *Maintenance of soil organic carbon in grain production* project used established research sites in Western Australia to examine the influence of farm management and environment on mechanisms driving carbon and nitrogen turnover. It also assessed the associated potential for greenhouse gas fluxes in grain production systems.

Key drivers determining soil organic carbon in the region are annual rainfall, temperature and soil type. Critical limitations for accumulation of soil organic carbon exist when average annual temperature is $>17.2^{\circ}\text{C}$, where rainfall is $<450\text{mm}$ and when soil clay content is low. Other influences included land sequence, soil pH, presence of stock and nutrients.

Accumulation of soil organic carbon where it occurs is slow and has relatively small market value. While critical to soil function, the adoption of farm management practices to build or preserve soil organic carbon must offer significant economic gains for unrelated outcomes, such as herbicide resistance management, resulting in more efficient and profitable systems. It is unlikely that soil organic carbon benefits will drive short-term practice change *per se* or increasing land values, but they may influence markets related to ecosystem or environmental value.

Input costs strongly influence the economic value of soil organic carbon, as does the

carbon price in an emissions reduction program and the cost of partial substitutes such as nitrogen fertiliser.

Key findings

Significance for Australian agriculture and landholders

- Climate is the primary determinant of soil organic carbon in Western Australia.
- Management changes resulted in small incremental gains in soil organic carbon (<0.1 to 0.3 tonnes carbon/ha/year). The resultant gain, if any, can often take decades to be measurable against background levels.
- While often not economically or practically viable, the addition of high amounts of organic inputs shows potential for accumulating soil organic carbon.
- Increasing organic inputs could increase soil acidification as a result of the nitrogen leaching associated with mineralisation of organic matter.
- In sandy soils prone to water repellence (predominantly <10 per cent clay), increasing soil organic carbon is associated with a higher severity of repellence.
- Improved water and nutrient use efficiency and the removal of constraints to plant growth and carbon stabilisation can help sustain the soil resource and maintain a viable agricultural sector.
- There was no productivity loss associated with increasing soil organic carbon and in some cases where large changes were generated, yields increased due to higher nutrient availability and changes in soil

water. However, practices were not always practical or profitable.

- Large variations in soil organic carbon and bulk density across a paddock contribute to sampling error, so short-term changes should be interpreted with caution.
- Increasing soil organic matter stimulated biological activity and function, and was critical to soil functions such as nutrient cycling, cation exchange capacity and water availability.
- Increasing net primary productivity through the removal of any agronomic constraints to production is likely to be the most profitable strategy to increase soil organic carbon.

Significance for Australian policymakers

- The adoption of practices solely for soil organic carbon accumulation in mainstream farming systems is unlikely without an agronomic or environmental benefit and associated market value. This could include access to niche or high value markets.
- More research is needed to determine the 'permanence' of any soil organic carbon changes.
- Potential for future carbon accumulation is more likely in subsoils below 0.1 metre.
- A dominance of soil organic carbon in the surface of Western Australian cropping soils suggests protection of the soil surface

from erosion is vital to prevent substantial carbon losses.

Implications

It is unlikely that soil organic carbon benefits will drive practice change or increases in land values in the short term, but may be influential where strong market signals related to ecosystem or environmental value are determined. It is important to note that the economic value is strongly influenced by the cost of inputs, in particular the price placed on carbon in an emissions reduction program, as well as the cost of partial substitutes such as nitrogen fertilisers.

Enhanced management of soil organic carbon to mitigate or decrease greenhouse gas emissions is challenging within the context of low rainfall dryland farming systems due to limitations in net primary productivity. While restricted in magnitude, there is potential given sufficient time for increasing net primary productivity and subsequent accumulation of soil organic carbon, but short-term responses to any productivity gains are unlikely.

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Seeding in stubble.

Carbon in eastern Australian farming systems

Background

Carbon in eastern Australian farming systems was a collaborative project aiming to provide evidence of soil carbon and nitrogen change under different management systems in eastern Australia, including Victoria, New South Wales and Queensland.

Key findings

- The effect of management is very small. Across the three states studied, it accounted for less than two per cent of the variation in soil carbon, compared with the 64 per cent linked to climate and soil.
- Cultivation and cropping of pasture soils reduced soil carbon and the loss increased the longer cropping was practised. Conversion of previously cropped sites to pasture could build soil carbon over the medium to long term. However, the longer the site had been cropped, the harder it was to increase carbon under grass pasture. The restoration of carbon during the grass pasture phase was not accompanied by restoration of nitrogen availability, an important indicator of potential productivity.
- Under cropping in Victoria and sugarcane in northern NSW, stubble retention and minimum tillage did not increase soil carbon.

- Under cropping in Victoria, inclusion of legumes in rotations with grain crops reduced soil carbon losses and increased soil nitrogen in some instances but not in others.
- In the grass-legume pastures of coastal NSW, soil carbon stocks increased as inputs of nutrients and irrigation increased, and the carbon stocks were positively associated with nitrogen availability.
- Under grazing in southern Victoria, soil carbon was not significantly affected by a range of phosphorus fertiliser or stocking rate treatments over 35 years, despite extremely large responses in pasture and animal production due to the treatments. Farmers cannot assume that increased production above ground equates to increased carbon storage in the soil.
- Results suggest that nitrogen addition would not be an effective practice for increasing soil carbon sequestration unless the soil is nitrogen-limited and carbon inputs are high.
- In southern Australia, soil carbon stocks were found to be lower in remnant native grassland than under agriculture due to phosphorus-deficient native soil. This contrasts to the common assumption that



New crop growing in previous year's stubble. Soil from the top 30cm.



Sampling a long-term cropping site.

conversion of native systems to agriculture invariably reduces soil carbon.

- Testing of the APSIM model against data from three long-term field experiments showed that model performance was generally good, although simplifications in the model meant that it may not always capture trends at specific locations.

Implications

The practice with the most potential to increase soil carbon sequestration is conversion of cropland to pasture, with increases in the order of 0.1 to 0.2 tonnes of carbon per hectare per year over about 20 years. However, the consequences of this transition for greenhouse gas emissions are uncertain. Differences in the carbon and nitrogen dynamics in cropping and pasture systems, and the introduction of livestock to pasture systems, mean that nitrous oxide and methane emissions need to be considered along with soil carbon.

Some other practices (legumes in crop rotations; fertiliser management in cropping and pasture systems; grazing management in pasture systems) may have potential to increase carbon sequestration, but further research is needed. There was no evidence that stubble retention and minimum tillage could increase carbon sequestration in grains cropping and sugarcane systems.

Productive agriculture was generally consistent with maintenance of soil carbon levels. Intensification of pasture systems to raise productivity (fertiliser, grazing, irrigation management) and conversion of Victorian native grassland sites to agriculture were observed to increase or not change soil carbon levels. Long-term cropping, however, reduced both carbon stocks and the productive capacity of the soil through fertility and soil structure decline.

The project supports the development of methodologies for the CFI/ERF by providing evidence of the effectiveness or otherwise of a range of management practices for increasing soil carbon.

This will help farmers and policymakers to make more informed assessments and decisions about soil carbon management, for greenhouse abatement and for maintenance of soil productive capacity.

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Increasing carbon storage in alkaline sodic soils

In the medium to low-rainfall regions of southern Australia, the productivity of crops and pastures can be constrained by the soil's chemical properties, which may limit the ability of farming systems to accumulate and retain organic carbon.

Soils in this region are predominantly alkaline, frequently sodic and many have high concentrations of carbonate salts.

The *Increasing carbon storage in alkaline sodic soils* project sought to examine whether pH could be manipulated to alter the accumulation or retention of organic matter in alkaline soils.

Dissolved organic carbon (DOC) plays an important role in the soil environment. DOC is only a small proportion of the total carbon pool in soil, but it is very reactive and highly dynamic. It facilitates soil microbial activity and can be an important source of mineralisable nitrogen, phosphorus and sulphur.

Key findings

- Variation in soil carbon stocks is unrelated to cropping intensity.
- There is an inverse relationship between the level of dissolved organic carbon and the yield within farming systems, which is consistent with a broader regional analysis of these alkaline soils.
- Variation in DOC is most strongly associated with pH and soil texture.
- Productivity is unrelated to the amount of organic carbon in the system, but is sensitive to the levels of DOC.



Gypsum trial plots at Minnipa, South Australia in 2014.

Historically, sodic, highly alkaline soils have been reclaimed by the planting of legumes and the application of gypsum. The study showed that at a pH of 8.5, applying gypsum:

- reduced pH
- reduced DOC
- had no significant effect on levels of soil organic carbon in most cases
- reduced potentially toxic water-soluble aluminium
- continued to show effects two years after application
- had an inconsistent effect on productivity
- had no influence on the uptake of soil nutrients by plants.

Implications

Significance to Australian agriculture

The work found that the concentrations of soil organic carbon were comparable to those previously reported for the region. The concentrations of DOC generally increased in proportion to the soil organic carbon concentration but there were several samples, particularly from the Eyre Peninsula, where concentrations of DOC were very high.

Dissolved organic carbon is a more sensitive indicator of the changes in farming systems than soil organic carbon and much more sensitive to variation yield. It is feasible to alter soil pH by using gypsum, but the long-term economic viability of this requires further work.

The frequency of water-soluble aluminium in alkaline soils and its documented phytotoxicity suggest it may be an important soil constraint in some highly alkaline soils. Developing crop and pasture varieties with a greater aluminium tolerance may contribute to productivity improvements and greater inputs of carbon to these soils.

The project also found that the characteristics



Sodic alkaline soils following sowing at the Minnipa gypsum trials.

of DOC were significantly influenced by agriculture land use. Concentrations of DOC were highest under intensive grazing and when additional straw was added, suggesting there were changes in the carbon dynamics under different systems but with relatively little impact on soil organic carbon concentrations.

Impact of the research on policymakers, industry and farmers

Increasing productivity is an effective way to increase soil carbon stocks. Poor productivity (around 50-60 per cent of potential yield) on sodic alkaline soils often limits carbon inputs. The work has demonstrated the feasibility of lowering pH by using gypsum and also identified threshold pH values where gypsum would be most beneficial.

Variation in soil organic carbon among different farming systems was only significant where there was frequent cultivation or where there was intensive grazing within the system. In no-till and reduced-till systems, there was no significant difference on soil organic carbon concentration or soil carbon stocks. This suggests that a potential way to improve carbon stocks in intensive cropping systems is to increase overall biomass production by overcoming important biotic and abiotic limitations.

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Native perennial vegetation

Building stable soil carbon and farm resilience

In low to medium-rainfall zones, rotational grazing of perennial native grasses is often seen as a way to improve the productivity and sustainability of these pasture systems. Theoretically, rotational grazing can increase pasture productivity relative to continuous grazing by allowing vegetation to recover after short intense grazing periods.

The *Native perennial vegetation* project sought to assess whether soil organic carbon stocks increase under rotationally grazed paddocks relative to typical set-stocked paddocks.

Several pairs of rotationally grazed and set-stocked paddocks were sampled for soil carbon in the mid and upper north of South Australia. These samples were then analysed for carbon content and allocation of carbon to fractions. By comparing data from the two types of grazing systems, researchers were able to assess whether there was a carbon benefit to adopting rotational grazing. They also examined whether soil organic carbon stocks would respond to the adoption of rotation grazing management in these regions.

The aim was to deliver the knowledge and tools needed for these extensive grazing systems to be able to participate in the Carbon Farming Initiative (CFI) through carbon abatement options if feasible.

Key findings

Soil organic carbon stocks in the 0 to 30cm layer varied four-fold across the study region, primarily as a function of climate and soil wetness. Despite substantial differences in management practices, which in some cases led to shifts in pasture productivity, there were no clear trends in soil organic carbon stocks.



Both rotationally grazed and set-stocked paddocks were sampled, and the samples analysed for carbon content and allocation of carbon to fractions. By comparing the data, researchers were able to assess whether there was a carbon benefit to adopting rotational grazing.



The *Native perennial vegetation* project sought to assess whether soil organic carbon stocks increase under rotationally grazed paddocks relative to typical set-stocked paddocks.

Two reasons were suggested for the lack of soil organic carbon response. First, changes in plant productivity and turnover in low-medium rainfall regions due to changes in grazing management are small and slow so, at best, only small incremental changes in soil organic carbon stocks could be expected. Second, there is inherent variability within and between paddocks, making detection of a small real change very difficult on short timescales.

Implications

A finding of no significant management effect on soil organic carbon stocks is important in the context of the CFI/ERF. Primary producers should not have false expectations based on anecdotal evidence.

Graziers will have a better understanding of the implications of different grazing management practices on soil organic carbon stocks in this region. The project's findings suggest that while carbon stocks vary significantly, management is not a driving factor in these differences.

While there are production and biodiversity benefits associated with a switch from continuous to rotational grazing, there does not appear to be much soil carbon benefit at least in the short to medium term (less than 15 years).

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Influence of grazing pressure on soil organic carbon

Total grazing pressure (TGP) – or the combination of domestic livestock, native and feral herbivores – is a substantial risk factor for reduced ground cover and soil erosion. The management of TGP is a major issue for pastoralists in southern Australian rangelands.

Feral goat numbers have increased exponentially since the Millennium drought and there is a public interest in ensuring that areas in western NSW are managed for TGP, both in terms of soil conservation and landscape resilience.

The *Influence of grazing pressure on soil organic carbon* project looked at whether rotational grazing, combined with exclusion fencing in high TGP density areas, could increase soil organic carbon and perennial and total ground cover levels. Increases in ground cover represent a significant potential to prevent the loss of soil through wind and water erosion.

The project examined 11 sites in total, three intensively. On the three major sites, different grazing management (with/without TGP fencing) was examined and compared to no TGP management for vertosol and kandosol soil types. On each site, the landholders aimed to manage their paddocks to get a uniform grazing impact and around 30 per cent utilisation. Each rotational grazing incorporated long periods of rest.



The management of total grazing pressure influenced the amount of ground cover. Paddocks with the lowest levels of soil carbon stocks had the highest amount of bare ground.

Key findings

- Rotational grazing combined with exclusion fencing (in high TGP density areas) can increase perennial ground cover levels by 10 to 30 per cent and increase total ground cover (perennial, litter, dung and cryptogam) by 20 to 40 per cent.
- Management of some vegetation and soil types can lead to significant differences in total organic carbon and carbon stock, which can increase organic matter supply and reduce soil carbon redistribution.
- Unmanaged areas that are exposed to high TGP have a large, significant, negative correlation with reductions in both ground cover and carbon stock, as well as on natural resource management and biodiversity.

Implications

Impact of the research on policymakers, industry and farmers

Management involving exclusion fencing (when TGP is high) and rotational grazing has clear natural resource management (NRM) benefits, such as floristic diversity, ground cover and soil carbon, as well as positive production outcomes.

The benefits of retaining ground cover in pastoral areas are often positioned in terms of maintenance of the ecosystem service of soil retention. This study also suggests that, after accounting for infrastructure costs associated with fencing or water management, comparable stocking rates can be achieved under rotational grazing compared to conservative continuous stocking. This implies that public investment in incentive funding to support development of infrastructure such as fences and water management systems may support landscape changes in ground cover. This would help to prevent soil erosion and increase soil carbon sequestration (or soil carbon retention), which is of both public and private benefit.

Impact of the research on the CFI/ERF and sustainable land use

This project provides evidence that soil organic carbon can be increased by reducing the total grazing pressure (by the exclusion of non-livestock) to provide a potential sink of CO₂. The information from this project provides a benchmark for soil organic carbon values for southern Australian rangelands. The data on relative soil carbon sequestration potential for different soil types will contribute to CFI methodology and future ERF soil carbon methodology using the FullCAM model, or its future extension.

Results suggest that grazing management may be useful in avoiding soil carbon losses by reducing erosion in rangelands. Despite the small quantities of soil carbon in these areas, the extensive areas covered by rangelands represent considerable mitigation potential through altered grazing management.

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By not aggregating soil samples collected at different depths, researchers were able to detect significant changes in soil carbon stocks at 0-5 and 5-10 cm depths in the soil profile.

Aboveground carbon inputs for carbon sequestration

The fate of aboveground carbon is poorly understood. The *Aboveground carbon inputs for carbon sequestration project* used isotopically labelled residues to measure how the addition of aboveground carbon added to soil carbon stocks. It also measured how the addition of carbon affected the emission of greenhouse gases carbon dioxide (CO₂) and nitrous oxide (N₂O).

Researchers designed different treatments to mimic agricultural practices such as tillage and crop residue retention.

Key findings

An increase in the amount of carbon applied (in plant residues) resulted in a corresponding increase in residue-derived soil carbon¹ content. However, it also resulted in an increase in the mineralisation of existing soil organic carbon through a priming effect and elevated N₂O losses. For example, in the high-input treatment there was a 21 per cent increase in the rate of existing soil organic carbon mineralisation and a 44 per cent increase in N₂O emissions compared to the control.

Similarly, the mixing of aboveground carbon with the topsoil (tillage) resulted in higher residue-derived soil carbon content. However, the majority of this (more than 60 per cent)

was in the active carbon fraction, meaning that it is easily accessed by decomposers and lost from the soil system as CO₂. Mixing of residues also resulted in an increase in the mineralisation of existing soil organic carbon (25 per cent) and elevated N₂O emissions (35 per cent).

Implications

Agricultural management practices, such as residue retention and no-till, are promoted as capable of offsetting greenhouse gas emissions because of their ability to store carbon in soils. This study, through the use of isotopically labelled residues, provided a unique insight into the contribution of aboveground carbon input to soil carbon stocks (active and stable carbon fractions) and their effect on greenhouse gas emissions.



Microcosms in the ground at Kidman Springs. Microcosms (PVC tubes, 10 cm in diameter) containing isotopically labelled plant residues were left to decompose in situ for 12 months. Microcosms were then removed intact and transported to QUT for analysis. Soils within microcosms were removed and fractionated into active and stable carbon pools and analysed using Isotope Ratio Mass Spectrometry (IRMS) to determine the fate of the applied residues in the mineral soil.



The growth chamber located at Queensland University of Technology, consisting of a sealed plexiglass unit where environmental conditions were monitored and controlled to ensure optimum growth. Plant biomass was grown in an atmosphere enriched in ^{13}C and fertilised with a nutrient solution enriched in ^{15}N . When plants reached maturity they were removed from the chamber and deployed to various field sites.

Significance of findings for Australian agriculture and specific industries

After 12 months, potential benefits of soil carbon sequestration from increased plant residue input were outweighed by priming of existing soil carbon and elevated N_2O emissions in three of the four treatments investigated. This means that current consideration and promotion of agricultural practices to increase soil carbon storage must consider changes beyond just the benefit of soil carbon sequestration.

Reducing GHG emissions and/or adapting to climate change

This project has provided valuable insight into soil carbon sequestration as a potential greenhouse gas mitigation strategy. It clearly showed that increasing carbon input on the surface (such as through residue retention) to increase carbon sequestration acts to prime existing soil organic matter, which may negate any intended carbon benefit and can actually lead to increases in net global warming potential over the first 12 months.

Researchers concluded that fostering carbon sequestration may be a tool for climate change mitigation, but that further investigation into the long-term, as well as the immediate, effects of different residue management strategies was needed.

Contribution to CFI/ERF methodology

The project provides a unique dataset that takes into account the effect of aboveground

carbon inputs on changes in carbon stocks. It quantifies poorly understood processes (i.e. the rate of movement of aboveground carbon and nitrogen and stabilisation rates in the mineral soil) and how carbon sequestration and the soil organic carbon pool allocation are affected by temperature, precipitation and soil type.

Consequently, the data will improve modelling capacities on the partitioning of carbon and will be integrated with existing models, primarily RothC and DayCent, to increase the accuracy of the way carbon/nitrogen transfers from the surface are represented. This will lead to more accurate predictions of soil carbon stock and CO_2 losses with changes in management practices.

More long-term studies are required to investigate the movement of aboveground carbon and its stabilisation into the soil and the net global warming potential under different management scenarios.

The promotion of increased soil carbon inputs in agriculture to sequester carbon needs further consideration.

1. Residue-derived carbon: carbon derived from residues that were applied to the land. Residues were isotopically labelled, which allowed researchers to distinguish between carbon applied in residues (5 per cent enriched in ^{13}C) vs carbon already in the soil (natural abundance of ^{13}C , <1 per cent).

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