Australian soil carbon stocks: a summary of the SCaRP program results

Introduction

In 2009 the Soil Carbon Research Program (SCaRP) was established as part of the Climate Change Research Program within the Australia's Farming Future initiative of the Department of Agriculture, Fisheries and Forestry (DAFF). SCaRP brought together soil carbon staff from a range of research organisations with regional representation to deliver a coordinated program of research on soil carbon. The program was administered and coordinated by CSIRO and although DAFF provided the major single source of funding, a substantial contribution was made by the Grains Research and Development Corporation (GRDC) and in-kind contributions were made by all research partners. Geographically, SCaRP projects were based in Queensland, New South Wales, Victoria, South Australia, Tasmania and Western Australia with links being formed with additional non-SCaRP projects in Northern Australia, New South Wales and Victoria.

SCaRP Objectives

At the onset of SCaRP, DAFF requested that a coordinated set of projects be developed that were consistent with national greenhouse gas inventory methodology, would aid in the development of emissions trading policy and could identify practical greenhouse gas mitigation programs. The emphasis of SCaRP was therefore directed towards acquiring soil carbon stocks data that would:

- Further develop and/or validate Australia's existing methodologies used in soil carbon accounting within the national greenhouse gas inventory program,
- Quantify existing soil carbon stocks in key soil types under important farm management regimes within some of Australia's agricultural regions.

In response to these requirements SCaRP established the following specific objectives:

- Development of a nationally consistent approach to assess soil carbon stocks for some of the major land-use/soil type combinations used for agricultural production in Australia.
- Assessment of rapid and cost-effective methodologies for quantifying soil carbon stocks and composition and for measuring soil bulk density.
- Identification of land-uses and management regimes with higher carbon stocks at a regional scale.
- Quantification of the inputs and fate of carbon to soils under agricultural systems based on perennial pastures.
- Provision of temporal soil carbon stock data for further development of FullCAM (Australia's national carbon accounting tool)

Considerations

The main soil collection and analysis activities conducted by SCaRP were completed on soil samples derived from farmer managed paddocks. It is important to recognise that the soil sampling conducted within SCaRP was not conducted to establish a soil monitoring program to quantify sequestration of carbon in soils. The three year duration of SCaRP, when considered in conjunction with the influence of climate variability on agricultural production and the slow rate of change of soil organic carbon stocks, would not allow estimates of carbon sequestration with high certainty to be derived. The collected samples therefore represented a baseline measurement of the soil carbon stocks within the various combinations of soil type by management regime investigated within each agricultural region. All sampling sites were georeferenced and for some sampling sites multiple soil samples were collected and analysed individually. The soil samples collected within SCaRP along with their associated meta and analytical data will be added to the national soil archive. This will allow future projects to return to the sites, collect new samples and quantify the magnitude and certainty of any soil carbon stock changes.

A minor, but important, additional soil collection activity involved the resampling of previously sampled field experiments. Resampling and analysing the soils from these experiments has provided temporal soil carbon stock data for eleven locations having a range of soil types and climatic conditions. This data will be available to validate and calibrate soil carbon cycling models in subsequent research activities.

An individual sampling site within SCaRP corresponded to a 25m x 25m area located randomly within a paddock. Each sampling site was considered to be a single representation of a defined combination of soil type and management regime. Multiple sampling sites were selected within a region and aggregation of the data collected across all sampling sites within a region provided an indication of soil and management impacts on soil carbon stocks. An individual 25m x 25m sampling site cannot be considered as representative of the entire paddock within which it resided due to the potential spatial variation in carbon stocks within paddocks. As a result, although appropriate for the purposes of SCaRP, the use of a 25m x 25m sampling site is not appropriate for the objective of defining carbon stocks over an entire paddock. In order to measure soil carbon stocks or stock changes over whole paddocks or farms, soil samples must be drawn from the entire area under consideration for entry into the carbon accounting scheme. Once appropriate sampling locations are defined, the methodologies used by SCaRP for collecting, processing and analysing soil carbon contents and composition and calculating soil carbon stocks are entirely applicable.

The number of samples collected and analysed by SCaRP (20,495 including the 2,774 provided by other projects) from 4,526 different locations, makes SCaRP the largest soil sampling exercise conducted for Australia in which all data required to quantify soil carbon stocks has been collected. The methodologies developed and data collected will be useful in generating additional outputs beyond those identified for the SCaRP itself. For example, the generation of maps of soil carbon stocks and composition and comparisons of measured SCaRP data with simulation model predictions. Such outputs, along with those provided by SCaRP, will be important to assessing and developing the FullCAM soil carbon modelling framework and to developing methodologies for the Carbon Farming Initiative. However, it needs to be acknowledged that SCaRP was not comprehensive in either the range of soils or management regimes examined. Agricultural regions where no sampling occurred will need to be incorporated into subsequent work. New and innovative approaches to improving agricultural production and the return of carbon to soils are constantly being developed by landowners and these will need to be continuously assessed across all agricultural regions.

Cost effective measurement of soil carbon contents and allocation

Mid-infrared spectroscopy combined with partial least squares regression analysis (MIR/PLSR) was used successfully to build models capable of predicting soil carbon contents and composition. National predictive MIR/PLSR models now exist for estimating the contents of total carbon (TC), organic carbon (OC), inorganic carbon (IC), total nitrogen (TN), particulate organic carbon (POC), humus organic carbon (HOC) and resistant organic carbon (ROC). Additionally it was found that improvements to the national models could be obtained by creating regionally specific models for TC, OC and IC. Further assessment of how to best optimise the prediction of soil carbon contents and composition is warranted.

The development of these MIR/PLSR predictive models provides a more rapid and cost-effective method of soil analysis than the traditional time consuming, labour intensive and expensive laboratory analyses. However, the uncertainty associated with the MIR/PLSR predicted values will be higher than that associated from the laboratory analyses.

When the MIR/PLSR predictive capacity for soil carbon is combined with previous work demonstrating an ability to predict soil clay content and other soil properties, the potential exists to derive MIR/PLSR estimates for the soil data required to parameterise the soil carbon model used by the National Inventory to define changes in soil carbon stocks. However, initial applications of the previously derived soil clay content MIR/PLSR predictive models suggest that further calibration and the development, such as that completed by SCaRP for soil carbon contents, is required to derive appropriate estimates of clay content for all Australian soils.

Automated measurement of soil bulk density

Two neutron density meters (NDM) were assessed in SCaRP projects: a soil surface based system and a core scanning system.

The surface based NDM provided values with virtually no soil disturbance, but was limited to a depth of 0.30 m and produced bulk density values for incremental depth layers were calculated by difference. The bulk density data obtained from the surface NDM and corresponding volumetric ring samples were not well correlated;

however, the surface NDM used a factory calibration. Calibration of the surface NDM to specific soil conditions (bulk density, clay content, gravel content and water content) may improve performance. Despite variations in bulk density, values calculated for carbon stocks using bulk density values derived using both the surface NDM and volumetric rings were not statistically different.

The core based NDM system can be used to directly measure the bulk density along the entire length of a soil core. However, it is reliant on the acquisition of an “undisturbed” soil core. Results indicated strong agreement between the directly measured values of soil bulk density and those obtained using the core NDM system after NDM calibration and applying water content corrections.

SCaRP results suggest that neutron density meters offer an alternative to the time consuming and sometimes very difficult manual measurement of bulk density. With adequate calibration they have the potential to replace manual measurements and warrant further study across a wider range of soil types.

Perennials

The C3/C4 transition project showed that the effect of perennial pasture on soil carbon stocks varies with pasture type and region. Kikuyu-based perennial pasture systems in the southern agricultural district of Western Australia and in Kangaroo Island and the Fleurieu Peninsula of South Australia had greater soil carbon stocks than adjacent annual pastures. The difference in soil carbon stocks between the kikuyu and annual pasture increased linearly with increasing age of the perennial pasture resulting in average sequestration rates of 0.90 ± 0.25 and 0.26 ± 0.13 Mg C ha^{-1} yr^{-1} in WA and SA, respectively. No changes in soil carbon stocks were found in kikuyu-based pastures in the Namoi Catchment, NSW. In the northern agricultural district of WA, perennial pastures based on a mixture of panic and Rhodes grass did not change SOC levels relative to annual grass based pastures.

Stable carbon isotope composition data collected for the kikuyu pastures indicated that gains in SOC stocks resulted from new soil carbon derived from the perennial vegetation concentrated in the 0-0.1 m soil depth layer. This data also suggested that in WA the soil carbon stock gain resulted from an accumulation of coarse particles of soil carbon typically associated with labile plant-derived organic materials. In the SA soils a greater portion of the accumulated perennial derived carbon was associated with the more stable forms of carbon associated with fine particles. Such differences suggest that there may be a difference in the long-term stability of the newly sequestered SOC between these two regions.

The $^{14}CO_2$ labelling studies showed that the proportion of captured carbon directed below-ground by growing Kikuyu pastures and Rhoades/pannic pastures in WA differed significantly (72% vs 43%, respectively). It was also shown that for the kikuyu pastures the majority of below-ground carbon (82%) was recovered in the 0-0.1m soil layer; while, for the Rhoades/pannic system, the majority of below-ground carbon (84%) was recovered in the 0-0.2 m soil layer.

Management impacts

A summary of the influence of land management practices on 0-0.3 m soil carbon stocks are presented in Table 1. On examining Table 1, two general conclusions arise:

1) No individual management practice has the same influence on 0-0.3m soil carbon stocks across all agricultural regions included in SCaRP.
2) Statistically significant differences in 0-0.3 m soil carbon stocks were often not detected despite strong variations in the management practices assessed (e.g. continuous pasture versus continuous cropping).

An inconsistency in the response of 0-0.3 m soil OC stocks to particular management practices across the projects and geographic regions was evident. For example, no statistical differences in 0-0.3m soil OC stocks were noted between continuous cropping, pasture and rotational cropping in the Murray Catchment of NSW; however, pasture soils contained more OC than cropping systems in the Central Slopes and Northern Slopes and Plains of NSW (Table 1). Part of this differential regional response to management may be attributed to variations in soil type as noted for Vertosols and Chromosols in the Northern Slopes and Plains of NSW and differential responses to pasture and cropping on Tasmanian Dermosols, Ferrosols, Vertosols and texture contrast soils. Variations in climatic regional properties may also play an important role in modifying the influence of management strategies on soil OC stocks. Soil OC stocks were positively correlated with the 30 year average annual rainfall in Central NSW and positive correlations with rainfall were also noted for Victorian and Tasmanian soils. Across the paddocks sampled in the Queensland cropping project, summer vapour pressure deficit and rainfall accounted for the greatest proportion of variation in 0-0.3 m soil OC stocks across the sites sampled. Such dependencies of soil OC stocks on soil type and climatic parameters may significantly modify the potential influence of particular agricultural management practices in their ability to alter soil OC stocks and at least partially account for the regional variations noted.

Statistically significant differences in 0-0.3 m soil carbon stocks were often not detected despite strong variations in the management practices assessed (e.g. continuous pasture versus continuous cropping) (Table 1). An inability to detect statistically significant management effects may occur where the variability between the samples collected for specific management treatments is high. An indication of the relative importance of this variation can be obtained by calculating coefficients of variation (CV) associated with average soil OC stocks. CV values calculated for the NSW samples were typically >0.20 and values as high as 0.49 were obtained. In a background of such high variability it will be hard to detect significant impacts of management on 0-0.3 m soil OC stocks.

Variations in soil type, climate and topographic properties within the regions sampled may have contributed to the high variance noted between sites within defined management practices. However, differences in the way individual landowners implement practices in response to personal preferences or business requirements may also contribute significantly. For example, consider the situation where the water use efficiency of continuous cropping systems ranges from 60% to 90% across a region due to landowner abilities and preferences. Under these conditions, differences in the input of carbon to a soil will result and soil carbon values will vary even under similar soil, climate and topographic conditions.

Table 1. Summary of the influence of agricultural management practices tested within SCaRP.

Project	Agricultural region	Summary of management effects on 0-0.3 m soil carbon stocks (values in parentheses are the carbon stocks, Mg C ha^{-1}, calculated on an equivalent soil mass basis using the 10th percentile of soil mass obtained for the sampling sites included in the identified comparisons)
MCMA	Plains	No differences were detected between continuous cropping (35.2), pasture (38.8) and rotational cropping (34.4).
	Slopes	Volunteer pasture (46.5) and introduced pasture (44.7) > continuous cropping (35.2) with differences confined to the 0-0.1 m layer.
NSW	Central tablelands	No difference was detected between high (42.2) and low (40.0) P fertiliser inputs to pastures. No difference was detected between set stocking (27.7) and rotational grazing (30.2).
	Central slopes	Permanent pasture (28.1) >Pasture in rotation (24.7) > Crop in rotation (21.6). No difference was detected between pasture cropping (32.2) and permanent pasture (31.1).
	Central plains	Pasture (21.7) > cropping (20.1).
	Northern slopes and plains - Vertosols	Native pasture (41.4) and tropical pasture (38.9) > irrigated cropping (23.6), cropping with tillage (23.2) and cropping with minimum tillage (24.6).
	Northern slope and plains - Chromosols	No differences were detected between native pasture (49.1), tropical pasture (43.7), cropping with tillage (37.8) and cropping with minimum tillage (40.7).
	Northern slopes and plains – pasture trial	No differences were detected between native grass (37.4), lucerne (39.9), Rhoades grass (41.9) and Premier digit (37.8).
	Northern tablelands	Improved pasture (45.9) and native pasture (43.3) > wooded systems (36.1). No difference was detected between cropping with organic fertilisers (41.3) and chemical fertilisers (40.7). No difference was detected between rotational grazing (50.2) and set stocking (44.2) pastures.
Qld Cropping	Hermitage research trial	No differences were detected between tillage, stubble and fertiliser treatments.
	Goodger research trial	No difference was detected between conventional tillage and no-tillage systems.
	Biloela research trial	No difference was detected between conventional tillage and no-tillage systems.
	Commercial farmer paddocks	Little impact of stubble management, tillage, crop type or fertiliser application. Average regional soil OC stocks for the south east, south west, north east and north west regions were 43, 27, 45, and 37 Mg C ha^{-1}, respectively.
	Sugarcane soils	No differences detected were between conventional tillage and no-tillage at MacKay and Ingham trials. No differences were detected between stubble retention and stubble burning at MacKay and Bundaberg trials. On commercial paddocks soil OC stocks only varied with sand content which accounted for 75% of the variation in soil OC stocks

Table 1. (continued)

Project	Agricultural region	Summary of management effects on 0-0.3 m soil carbon stocks (values in parentheses are the carbon stocks, Mg C ha^{-1}, calculated on an equivalent soil mass basis using the 10th percentile of soil mass obtained for the sampling sites included in the identified comparisons)
Qld Rangelands	Tarook pasture utilisation trial	A 20% grazing intensity (13.9) gave a higher soil OC stock than 80% grazing intensity (12.4) at p=0.10.
	Kidman Springs fire management trial	Within the each of the two soils, no differences were detected between the applied fire management treatments but there was a soil type effect.
	Wambiana grazing trial	No differences were detected between grazing pressure treatments on SOC stock, but there was a soil-type effect.
	Grazing management sites	Little impact of cell, rotational or continuous grazing management practices but 10 year average stocking rate had a negative impact on soil OC stocks possibly through its impact on total shoot dry matter.
SA	Red-brown earths from Mid-North and Eyre Peninsula regions	No clear effect of agricultural management class (cropped vs crop-pasture rotation vs pasture) on soil organic carbon stocks could be detected.
Tasmania	Commercial paddocks	Differences in soil carbon stock were noted between pasture and cropping paddocks for Dermosols (102 vs 83), Ferrosols (150 vs 125), Vertosols (107 vs 96) and Texture contrast soils (65 vs 58). Cropping frequency and tillage intensity were found to explain a portion of the variance in soil OC stocks but were not an influential as soil type, rainfall or landuse.
Victoria	Hamilton Long-term Phosphorus Experiment,	No differences were detected due to phosphorus application or stocking rates.
	Ararat grazing management trial	No differences were detected between continuous grazing (63), optimised deferred grazing (50) and timed grazing (61).
	LR1 cropping trial near Horsham	Soil organic C stocks were greater in the Pea-wheat-barley (30) and Pea-wheat-oats (27) rotations than in the others (Fallow-wheat-oats(22), Fallow-wheat-oats-pasture(22), Fallow-wheat-pasture(25), Wheat(24), Wheat-fallow(23)).
	SCRIME trial near Horsham	No differences were detected between applied stubble management and tillage treatments (range of soil OC stocks was 22.4-25.8).
	MC14 trial near Walpeup,	No differences were detected between rotation and tillage treatments (range of soil OC stocks was 17.0-22.2).
	Wimmera Recharge trials (Antwerp and Boolite)	Antwerp – lucerne (28.4), tagasaste (28.0) and salt bush (28.9) > chemical fallow (22.4). Boolite – native grass (35.5), tagasaste (31.5) and salt bush (32.2) > chemical fallow (24.5).
WA	Esperance	No difference was detected between annual pasture (43) and perennial pasture (43).
	Albany	Perennial pasture (97) > annual pasture (73) > mixed cropping (43) and continuous cropping (37).
	Kojonup	Mixed cropping (69) > permanent pasture (58).
	Geographe	No differences were detected between beef grazing (86), beef hay (82), dairy grazing (99), dairy hay (86) and dairy irrigated (91).
	West Avon Basin	Annual pasture (25) and mixed cropping (24) > continuous cropping (20).
	Stubble retention trial – Merredin	No difference was detected between stubble retained (32.2) and stubble burnt (28.7).