Section Two

Cropping Systems

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Changes in Carbon in Summer Rainfall Cropping Systems

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Australian Commodity Statistics (ABARE) report land use in 1990/91 as 9.2 m ha wheat, 8.2 m ha of other crops, and 28.3 m ha of sown pasture. The other crops component included 4.13 m ha coarse grains, 1.38 m ha pulses, 0.59 m ha oilseeds, 0.34 m ha sugar cane, and 0.09 m ha rice. The trend lines for each suggest the area of wheat increasing by 50%, oilseeds, pulses and rice doubling, and sugar cane should increase to about 0.4 m ha by year 2000. This expansion is often in drier, more marginal areas, so it could be difficult to demonstrate that significant carbon sequestration is possible in Australian farming systems.

Cropping Systems in the Northern Grains Region of Australia

Soil and climatic limitations strongly influence crop production options and the specific practices that are employed. Clear differences exist between the temperate winter-dominant rainfall regions of southern NSW, Victoria, South Australia, and Western Australia compared to the summer rainfall areas in northern NSW and Queensland. The >50% summer rainfall region is north of Dubbo in New South Wales. Rainfall is unreliable, and fallowing is required in many areas to increase yield potential and to reduce uncertainty.

Much of the land used for cropping had to be cleared of trees and shrubs. Cultivation is used to control weeds but this can reduce soil structure, and cause soil compaction. A decrease in profitability in livestock enterprises during the last few decades has resulted in an increase in cropping on many farms. Improvements in mechanisation, bulk handling of grain and fertilisers, and a greater range of herbicides, also have contributed to this trend. Herbicides have been paramount in reversing the reliance on tillage to control weeds, particularly in those areas where fallowing is virtually a prerequisite to obtaining reasonable production. But these bring new problems. Greater emphasis on using herbicides to control weeds has the inevitable outcome that naturally tolerant species will become more common and that herbicide resistance will develop. Inappropriate use of herbicide-tolerant crops could escalate these problems.

One way of improving our cropping systems has been to retain more crop residues on the soil surface, and to reduce tillage to maintain ground cover for a longer duration. Achieving and maintaining adequate ground cover is not always possible, particularly with annual cropping. Rainfall and temperature strongly influence plant growth and the amount of material remaining after harvest, and also the rate of decomposition of these residues. Areas of lower rainfall and higher temperatures have less biomass accumulation and also lower inherent soil organic fertility. Therefore, expansion of cropping into the more marginal areas might make it more difficult to achieve sustainable systems.

CROPPING SYSTEMS RESEARCH

Over the last two decades experiments concentrated on summer fallow management between winter annual crops, more diverse crop rotation, and cereal crop yield optimisation through nitrogen fertiliser application. Specifically, no-tillage was compared with conventional tillage with and without retention of cereal stubble. After 15 years of stubble retention there was 2 t/ha more soil organic carbon in the plough layer compared to where the stubble was burnt after harvest. Up to 1.5 t/ha more carbon resulted from no-tillage compared with cultivated fallows (Schwenke, unpublished data). When the same comparisons are made using just the fraction of soil organic matter that is most affected by management, as opposed to the whole organic matter which includes much that is recalcitrant, the treatment effects become more consistent across the different trials. At two experiments at North Star sampled after 5 years of no-tilled or cultivated fallows, there was a 0.7–0.8 t/ha difference in organic carbon in the top 10 cm of the soil.

In adjacent experiments at Tamworth, one on a red clay and the other on a black clay, Blair and Crocker (2000) reported no significant differences in total carbon between treatments after 30 years. Treatments were (a) long fallowed between wheat crops, (b) three years lucerne pasture followed by three years wheat, (c) medic pasture/wheat rotation, (d) grain legume/wheat rotation, (e) medic pasture/wheat rotation, or (f) continuous wheat. On the black clay, the medic rotation led to higher total soil carbon than either a grain legume or long fallow rotations.

More attention needs to be directed towards summer crops such as sorghum and maize. Being C4 plants, these have a greater potential for C accretion than C3 plants such as wheat. In addition, summer cropping is thought to be less exploitive than winter cropping and summer fallowing because these keep the soil drier and cooler during summer when most organic matter mineralisation occurs (Grace *et al.,* 1998). In areas such as the Liverpool Plains, grain sorghum yields >8 t/ha are not uncommon, which gives a potential carbon residue above ground in the order of > 6 t/ha. This amount, even after discounting that which is oxidised as the plant material breaks down, is still above the loss of native soil organic matter over the growing period. In southern Queensland, Saffigna *et al.,* (1989) and Standley *et al.,* (1990), found that annual retention of at least 4 t/ha of sorghum residues was necessary to balance soil carbon mineralisation in vertosols.

Cropping has expanded in the lower rainfall areas (<600 mm) of northern NSW. It is likely that cropping cannot have the same intensity as it has in the higher rainfall areas, so pastures should play a greater role in rotations. Chan *et al.,* (1995) in a 5 year experimental program near Walgett, found that organic carbon increased by up to 26% in a brown clay soil under grass-legume pasture, but no increase was recorded on a grey clay. In contrast, continuous cropping on the same degraded soils caused no further decline in soil organic carbon levels.

The effect of minimising tillage and using cotton-based crop rotations on carbon sequestration in irrigated Vertosols was evaluated from 1993 to 1998 in several experimental sites in northern NSW. Carbon sequestration was highest where minimum tillage and rotation with wheat had been practiced for extended periods, >10 years. In the short-term, <5 years, replacing intensive tillage with minimum tillage resulted in a fall in soil carbon sequestration. This was attributed to the low decomposition rate of cotton crop residues. Significant differences were also absent between crop rotations, for example, cotton-legume and cotton-cereal, with respect to short-term carbon sequestration (Hulugalle, 2000).

In southern Queensland no-tillage, crop residue retention, and fertiliser N application increased organic carbon in the top 10 cm by 2.8 t/ha over 13 years of continuous cereal production, compared to soil that had been tilled, stubble burned and with no N fertiliser (Dalal 1989). Tillage effects extended to a depth of 20 cm. Over the next seven years, carbon levels generally continued to increase, although levels "dipped" when no crop was grown in one year (Dalal *et al.,* 1991). Tillage intensity and fertiliser nitrogen application had little impact on soil carbon storage in the following rotations; lucerne/wheat, medic/wheat, and chickpea/wheat. But two year rotations of grass/legume pastures with wheat increased organic carbon by 20% in the top 2.5 cm of the soil compared to continuous wheat (Dalal *et al.,* 1995).

Lighter-textured soils, <30–35 % clay, make up more than 80% by area of cropping soils in Australia (Chan *et al.,* 1998). Many have inherent soil physical problems, for example, hard-setting, sodicity, and low organic carbon levels. Maintenance and improvement of soil organic carbon levels (SOC) are crucial to preserving the soil structure and physical fertility of these soils. A review of field trials on conservation tillage, 3–19 years duration, on light-textured soils around Australia revealed that significant increases in SOC levels compared to conventional tillage were found only in the wetter areas (>500 mm) and the increases were restricted to the top 2.5–10 cm. No sites with rainfall <500 mm recorded increases in SOC under conservation tillage. The lack of a positive response to conservation tillage was probably a reflection of a number of factors, namely low crop yield due to low rainfall, partial removal of stubble by grazing, and the high decomposition rate due to the high temperature. There is evidence suggesting that under continuous cropping in the drier areas, SOC level continues to decline, even under conservation tillage.

Carbon Balances

THE NEED TO INCREASE LIVING BIOMASS

Policies that account better for farm, catchment, state and national vegetation management are needed. It will take considerable effort to achieve agreement at federal, state and local levels of government that will see custodians of the land implement strategies that will reverse farming practices that degrade the environment. These strategies may involve additional costs, and less production of some enterprises, which to an already struggling sector will lead to slow adoption. It is difficult to conclude that there will be any "quick fix solution". Options to consider include planting trees or shrubs:

- for forest products,
- for conservation/environmental/amenity purposes,
- around sheds, along internal roads, riparian and steep areas,

- to maintain productivity of enterprises elsewhere on a property or catchment,
- on degraded areas, where production from current land use is declining,
- for agroforestry reasons as a replacement for existing enterprises,
- on low production areas where agriculture is no longer profitable, for example, salt tolerant grasses/shrubs on saline areas, and serrated tussock infested areas.

THE NEED TO REDUCE EMISSIONS FROM PLANT RESIDUES

Plant nutrition requires residues to be decomposed, but for maximum soil C, slower breakdown is desirable. Farming systems can be manipulated to get a better balance and practices that lead to increased accessions of C & N include:

- eliminate burning; CO_2 or CO from burning are not accounted for in greenhouse budgets since they are only recycling C taken up earlier – maybe they should,
- incorporating stubble or retaining residues on the soil surface,
- changing the proportion of crop/pasture—but which is the greater contribution after allowance is made for methane produced by grazing animals?,
- reduced grazing intensity.

INCREASING BIOMASS WITHIN SOIL

Options include growing crops specifically for incorporation, green manure crops, or pasture with reduced grazing. Reducing cultivation and fallow length can have a positive effect. Liming acid soils, or leaching soil nitrate to greater depths in the profile, might increase soil biomass, but may not reduce gas emissions.

REDUCING ENERGY INPUTS USED FOR CROP PRODUCTION

The most likely benefits relate to machinery use and include:

- minimum/no-tillage to reduce the number of cultivation operations,
- reduced overlaps in operations,
- tram-lining or guidance systems,
- optimum size and rate of operation,
- farm layout to minimise internal travel.

Also increasing the efficiency of the fertiliser used by the crop by:

- reducing transformation to N_2O,
- increasing the supply of legume N,
- selecting the most suitable type for the conditions,
- better placement, and/or split applications,
- soil and tissue testing to match production requirements.

CHANGING MANAGEMENT PRACTICES TO INCREASE SOIL CARBON STORAGE

Information on how crop management practices affect soil carbon is limited (Carter *et al.,* 1997; Grace *et al.,* 1998; Chan *et al.,* 1998), and Australian Journal of Experimental Agriculture, 35 (Special Issue on Long-term trials around Australia, 1995) so more data would be helpful. Carbon accounting should also include considerations of the effects of agronomic practices on inorganic carbon stocks, and the contributions of grazing animals and their management, on carbon emissions from a given area. Crop management practices that influence soil carbon include:

- Fallow management where burning, reducing the number and severity of tillage operations, use of herbicides, retaining crop residues on the surface and shorter fallows are the key issues.
- Crop rotation with crop selection, possibilities to sow opportunity crops, and pasture leys provide greater biodiversity.
- Crop nutrition is a common problem with fertiliser application, need for green manure crops, ameliorating acidity or sodicity, organic farming just some of the issues to be considered in optimising crop needs.
- Paddock management concerns controlled traffic, precision systems, contour banks, waterways, windbreaks, strip cropping, and grazing options for mixed farms.
- Integrated weed and pest management can be most significant components with respect to both production costs and in achieving yield potential.
- Agroforestry is receiving more interest from farmers and has considerable potential to increase carbon stocks across the agricultural sector.

Strategies to increase carbon sequestration need to increase crop or pasture biomass production, and reduce carbon losses from slowed organic matter decomposition and topsoil retention. An increase in carbon storage requires there to be greater inputs of carbon than outputs over a given time period. Defining this time period is essential to calculate and measure carbon balances that are to be used in any form of policy-making activity. In the context of global change the time scale must be reckoned with larger time scales than those used in agricultural studies (Greenland, 1995). Because of the inherent variability of carbon in soils, significant changes are often difficult to measure in the field over a short time period. System modelling therefore can play a significant role in putting numbers on carbon flows where field measurement is problematic, but the existing suite of models does need greater fine-tuning through more process-level research. More measurement and monitoring of sites may be required to validate these models.

A soil carbon balance needs to consider:

CARBON OUTPUTS

1. Loss of carbon from the soil organic matter cycle:
   - decomposition of soil organic matter and freshly added residues releasing CO_2 to the atmosphere. In the oxidative conversion of organic inputs to humus by soil micro-organisms, 80–90% of above-ground C, and 50–80% of below-ground C, is lost as CO_2 to the atmosphere (Nye and Greenland, 1960).
   - leaching of organic compounds into ground water.
   - erosion of the organic matter-rich topsoil.
   - burning of crop residues and other biomass, for example forest trees and grasslands when clearing land for cultivation.
   - reduced inputs through product removal (harvested grain, baled stubble, grazed stubble) and changed plant systems such as conversion of forests, grasslands or perennial improved pastures, to annual cropping systems.
2. Loss of inorganic carbon from the soil. In soils, carbon exists in both organic and inorganic forms. In alkaline soils, such as those occurring widely in northern NSW, levels of inorganic carbon may be 10 times greater than organic carbon. Acidification of these soils through various cropping practices, for example, intensive use of legumes, buildup of soil organic matter, or leaching, may lead to significant release of CO_2 to the atmosphere.
3. Loss of carbon during management of soil:
   - emission of carbon by vehicles,
   - emission of carbon from decomposing pesticides,
   - release of CO_2 from the soil during and after ploughing, or other soil disturbances,
   - methane emissions from cultivation of flooded soils as occurs in rice paddies or poorly-drained soils.
4. Carbon loss from grazing animals as CO_2 respired, and methane from ruminant animals.

CARBON INPUTS

1. Inputs to the organic matter cycle:
   - photosynthetic plants using CO_2 from the atmosphere,
   - applying plant mulches, animal manures and composts.
2. Natural additions of inorganic nutrients from rock weathering.

MEASURING CARBON

Most studies on agronomic practices have considered just the net effects by comparing soil organic carbon levels before and after agronomic treatments were imposed. Separating contributions to inputs and outputs from the component processes is more difficult and beyond the scope of many projects. These have not been concerned with carbon accounting but with land sustainability issues related to soil organic matter.

There is a practical upper limit to the quantity of carbon able to be sequestered in agricultural soils as a result of following these practices which is determined largely by climate (rainfall and temperature) and topography, especially drainage. The closeness of current soil carbon stocks to the "carbon carrying capacity" of soil will determine the potential for carbon sequestration. Obviously, a more degraded soil in terms of organic matter level will have greater potential for sequestration than one which has been better managed or cropped for a longer period of time, typically under a regime that was degrading soil organic matter.

Future Requirements

The existing data are useful but have been collected for different purposes. Focusing specifically on carbon budgeting will require additional information, especially effects on soil inorganic carbon, and emissions of carbon as a result of grazing and machinery-based management practices.

Future research needs to focus on carbon sequestration under management that incorporates all "best management practices" where crops can achieve their full production potential.

System modelling requires fine-tuning through process-type research of the various avenues of carbon loss, and input under various conditions. These models also need extensive field validation across the state, both in research experiments such as long-term trials and through monitoring on-farms. A carbon accounting unit should be established within NSW Agriculture to coordinate these activities across the state, particularly ensuring that future field measurements are more scientifically sound and the data are credible for use in carbon accounting.

SOURCES OF ERROR

There are several major sources of error that contribute to the overall variability of soil carbon estimates. First, soil carbon levels in the soil are inherently variable. In a farm survey, Schwenke *et al.,* (1997) found greater variability in soil organic carbon within a paddock than between paddocks that were grouped by district. Variability within paddocks is exacerbated in row crops, especially where plant residues are returned unevenly at harvest. Such variation in organic matter is often ignored in field studies where too few individual samples, often only one, are collected from a paddock. Schwenke's 1997 study of field variation showed that collecting less than five samples gave unacceptably high within-paddock variation. Many past studies only have considered a single surface soil layer for comparison of agronomic effects, which ignores the potential for management influences to extend below the immediate soil surface.

Accurate assessment of soil carbon requires measurement of soil bulk densities when samples are taken from the field. Unfortunately, this aspect has been largely ignored in many studies. This is particularly relevant in studies comparing conventional with conservation tillage where differences in soil management can significantly alter soil bulk density, either directly through soil compaction, or indirectly through different soil moisture regimes at the time of sampling. Ellert and Bettany (1995) showed that many "significant effects of changed tillage practice" were nullified after comparisons on an "equivalent soil mass" basis which gives proper consideration of altered bulk densities.

After sampling, the next major source of error in measurement of soil carbon occurs in the treatment of the soil samples before analysis. Standard soil analysis methods specify removal of 'rock fragments' which may contain carbonates, and all visible plant remains such as roots and incorporated shoot material from the sample before grinding. Soil organic carbon, typically in the range 0.5–2%, can be markedly affected by even small additions of plant material with a carbon content of 40–50%.

Measuring soil organic and soil total carbon in laboratories are subject to inaccuracies in the order of between 10 and 30% for surface soils (Greenland, 1995). Most studies conducted in the past decade or so used automated combustion analysers that fairly accurately report total soil carbon. Prior studies made use of dichromate oxidation that only measured soil organic carbon, and even then, often gave incomplete recoveries. Part of this margin of error involves the recovery of unknown amounts and proportions of inorganic carbon such as $CaCO_3$ and charcoal, included in analyses of soil organic carbon. Analytical inaccuracies can be affected also by soil type. For example, high levels of iron or chloride in soil interfere with the accuracy of organic carbon analysis by dichromate oxidation methods.

CARBON CREDITS

Accounting for "credits" for carbon stored in soil requires paddock-scale information. In consideration of a nationwide carbon budget as part of a commitment to the Kyoto Protocol, a broad region account balance is needed. But the latter has such huge sources of error to be of little value other than to give broad estimates. This is especially the case for carbon accounting as much depends on inherent and dynamic soil characteristics, and agronomic management. Scaling this type of information up to a whole cropping region is highly tenuous, especially at this stage where the existing information has largely come from sparsely located long-term trial sites, many of which are situated on research stations. Only when carbon balance information becomes more widely available from a range of on-farm situations under farmer management, will cropping-region figures of carbon stock improvement be realistic. Furthermore, on a regional basis, small gains by improved crop management practices may be dwarfed by a dramatic increase in carbon losses as a result of clearing large areas of native forest, woodlands and grassland in areas of expanding cropping, such as western NSW.

Measuring carbon in soil and plants, estimating the change in carbon according to alternative uses of land, and of deriving cost effective monitoring systems at the decision-making level, is necessary for the Kyoto Protocol decision to be implemented. The critical question is whether resource users will have an incentive to change in a manner that will achieve the Government's objectives. Asset owners and managers will not act out of charity in making changes that will affect the profits of their enterprises and the livelihoods of their families.

The decision to change land use will be an economic one with prices and other incentives vital if change is to occur. An important issue for research is an economic evaluation of the present and likely future signals that farmers receive via the price system. The potential for carbon trading to benefit farming and forestry, and the demand for and supply of carbon credits, will provide an idea of the size of the actual credits. The likely change in land use under such a trading system will need to be compared with the status quo. If there is a difference which mitigates change, then governments will need to consider whether this constitutes a sufficient market failure to make policy that actively encourages the desired land use change.

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Management Options for Carbon Sequestration in Tropical and Sub-Tropical Cropping Systems

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Carbon Sequestration in Ecosystems

The carbon stored in an ecosystem comprises that held in vegetation (above and below ground) and in the soil (where both inorganic and organic forms can be present). In forestry systems there can be significant changes in C in the vegetation store, but in cropping systems the vegetation pools are small and transient compared with the soil store. It is the soil organic store that is responsive to management and provides potential for sequestration of C. Inorganic C (carbonate) is only likely to be important in greenhouse gas considerations where liming materials are being applied to ameliorate soil acidification.

The amount of organic C in soil (SOC) can be understood in terms of the inputs and outputs. The inputs are derived from plant/animal residues including roots. A major difference between natural ecosystems and agricultural systems is that part of the carbon fixed into vegetation is removed as product.

The outputs are the decomposition (mineralisation) of soil organic matter. This is usually considered to follow first order kinetics with the rate of decomposition determined by abiotic factors (temperature and moisture) and tillage.

Thus,

$$\begin{aligned} d(SOC)/dt &= \text{inputs} - \text{outputs} \\ &= f\{\text{NPP, harvest index}\} - SOC * f\{T, M, \text{tillage}\} \end{aligned}$$

This model for SOC leads directly to the notion that under uniform management conditions any system will tend towards a steady state content of SOC that is dependent on the inputs and outputs. It should be noted that the inputs are not directly identifiable with crop residues. These must undergo decomposition (with loss of some C) before becoming an input of soil C. Typically ~60% of residue C is evolved as CO_2 upon transformation into soil microbial biomass, and a similar proportion may be lost when Soil Microbial Biomass (SMB) is synthesised into the more stable forms that comprise the bulk of SOC. Thus the input as SOC may be some 10–20% of the total crop residue C.

It also follows that the quantity of inputs needed to maintain a unit of SOC is greater where the decomposition rate is high. So for a given input, tropical systems (warmer and sometimes wetter) will have lower SOC than temperate systems (eg Spain *et al.*, 1983).

This simple model does not include erosion. Loss of surface soil that is relatively enriched in soil organic matter does constitute a loss of SOC from a point location and thus will be a factor that affects measurement of SOC at a particular site. However erosion involves transfer of SOC from one location to another and *per se* has no direct effect on total C store of the larger system that embraces both the source and sink of the erosion deposits.

In terms of changing management with a view to sequestering additional C, there are few options for manipulating the "outputs". Management of surface residues can have some effects on temperature and moisture, whilst irrigation will be expected to increase soil water and thus rates of decomposition. Tillage is the only other option (more on this below).

On the "inputs" side there are more possibilities for sequestering C. These can be identified as:

- More crops, for example fewer or shorter fallows, double cropping,
- Bigger crops, implying that the factors (nutritional, physical, hydrological) that are limiting yields can be rectified,
- Management of residues, especially whether they are retained in situ or removed,
- Tillage effects on crop yields,
- Different crops. Perennial crops will generally fix more C than annuals because they are growing for a larger portion of the year. Alternative crops may return a higher proportion of net primary production to the soil as residue.

This provides a useful framework for examining current or alternative cropping systems to identify potential for C sequestration.

There are essentially two issues:

1. the amount of C that can potentially be sequestered is the difference between the steady state C content for the given system (that will ultimately be attained) and the present C content of the soil. Very few reports of changes in SOC have interpreted response to management in terms of the initial SOC content of the soil when alternative managements were imposed.
2. the rate at which SOC content changes in response to imposed management.

TILLAGE

There are conflicting reports in the literature on the effects of tillage on SOC. It is frequently stated that cultivation accelerates the breakdown of SOC (eg Rasmussen and Collins, 1991). However experimentally it is very difficult to separate the effects of tillage from other residue management effects (incorporation vs surface mulch) and the consequential changes to soil temperature and moisture. It is usual to hypothesise that cultivation increases rate of decomposition of SOC by increasing surface area and/or promoting microbial activity. Measured effects comparing different tillage treatments will also be confounded with decreases in SOC due to higher rates of erosion following cultivation.

Management Options for C Sequestration within Production Systems of the Tropics and Sub-Tropics

SUGARCANE SYSTEMS

Sugarcane is grown along the coastal strip from northern NSW to north Queensland, and there is an expanding industry in the Ord. The total area presently under sugarcane is ~ 500,000 ha. Sugarcane is a perennial crop that is harvested approximately on an annual cycle (except in parts of the cooler southern districts in NSW where the cycle is 2 y). There may be up to six ratoons before re-planting. There is generally only a short fallow (up to 6 months) between plough-out of the old cane and re-planting. On most farms sugarcane is grown as a monoculture, although leguminous cover crops are sometimes used in lieu of the bare fallow. In some districts (e.g. Bundaberg), sugarcane forms part of a land use sequence that includes horticultural crops (e.g. tomatoes, capsicums, melons etc), but the areas involved are relatively small.

The main feature of the sugar production systems that is pertinent to C sequestration is the advent of green cane harvesting trash blanket (GCTB) management. The system was first introduced in far north Qld the mid-1970s to facilitate wet weather harvesting (Wood, 1991); it also reduces costs of cultivation and weed control. Since then the system has been adopted further south, with widespread adoption in the Herbert Valley in the 1980's and in the Mackay and Bundaberg regions in the 1990's, so that it is now the normal practice in most regions within the industry. The exceptions are the Burdekin region, where use of furrow irrigation is inconvenient with trash blanketing, and parts of northern NSW where there are concerns about delayed crop development in cool conditions with trash blanketing.

Typically, GCTB results in some 10–15t/ha of crop residues being returned to the soil surface (Wood, 1986; Robertson and Thorburn, 1999) with little or no tillage during the crop. This contrasts with the alternative system where cane is burnt before harvest (removing dead leaves) and residues (green leaves) remaining after harvest are raked and burnt, so there is very little carbon (< 10 % relative to GCTB) returned to the soil from the above ground vegetation (Mitchell *et al.*, 2000). There may be tillage to control weeds in the burnt system.

The effect of GCTB has attracted considerable interest because of the expectation that it will result in increased SOC and in the longer term reduce the N fertiliser requirements of the crop (Wood 1986). SOC has been found to increase in the surface soil after 2–3 y of trash blanketing (Wood, 1991; Robertson and Thorburn, 1999), although detailed sampling (to 1.5 m depth) has shown that significant increases are confined to the top 0–20 and 20–50 mm soil depths (Thorburn *et al.*, 2000). The increases (GCTB–burnt) in SOC at different sites (Figure 1) ranged from 0.2–0.7 % in the uppermost 0–20 mm layer, and were not simple functions of time (1–17 y), initial SOC (1.1–2.5) or soil type (Thorburn *et al.*, 2000). In contrast to the GCTB system, SOC of surface (0–150 mm) soil of the burnt system declines relative to uncultivated land (Wood, 1985).

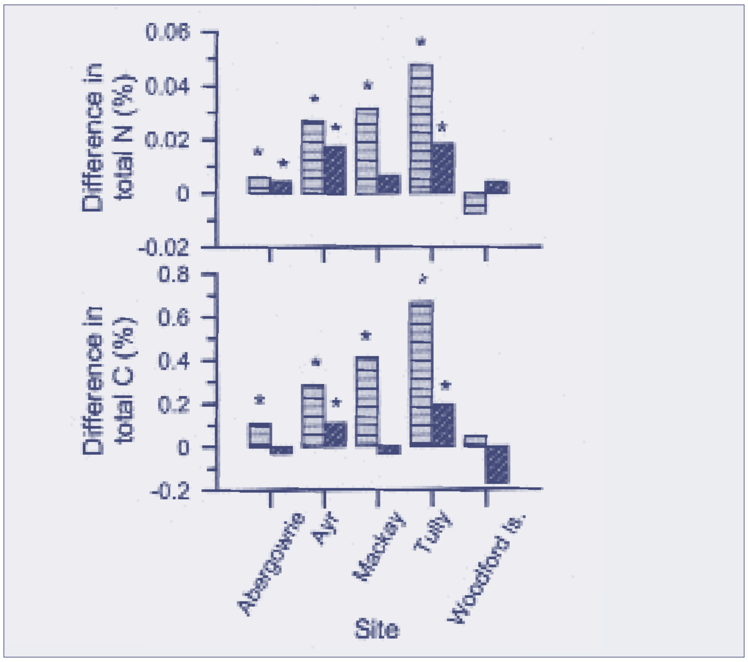

Figure 1. Effect of GCTB relative to burnt cane management on organic carbon and total nitrogen in soil at 5 sites. The left hand bar (horizontal stripes) refers to 0–20mm and the right hand bar (diagonal stripes) to 20–50mm. *'s indicate significant differences between treatments ($p<0.05$). The experimental period (y) between imposing the treatments and measurement was Abergowrie 17; Ayr 9; Mackay 5; Tully 6; Woodford Island 1.

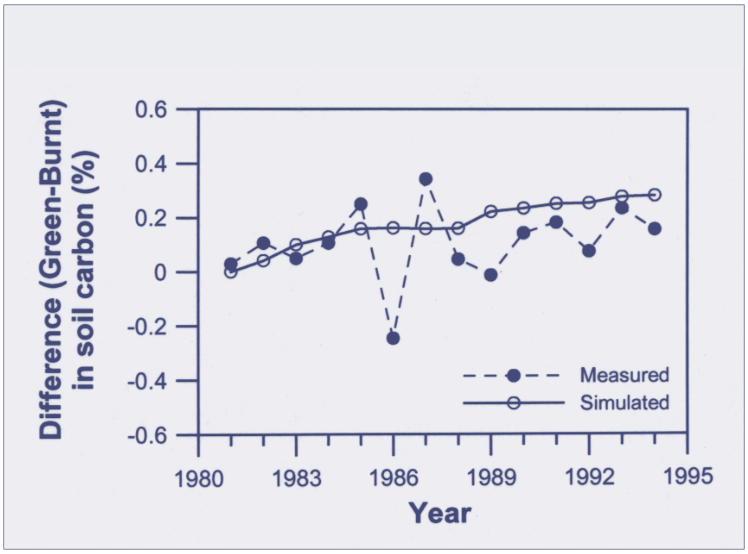

Figure 2. Measured and simulated differences in total soil carbon between GCTB and burnt trash management treatments in the 0–0.2 m soil depth. From Thorburn *et al.,* (1999).

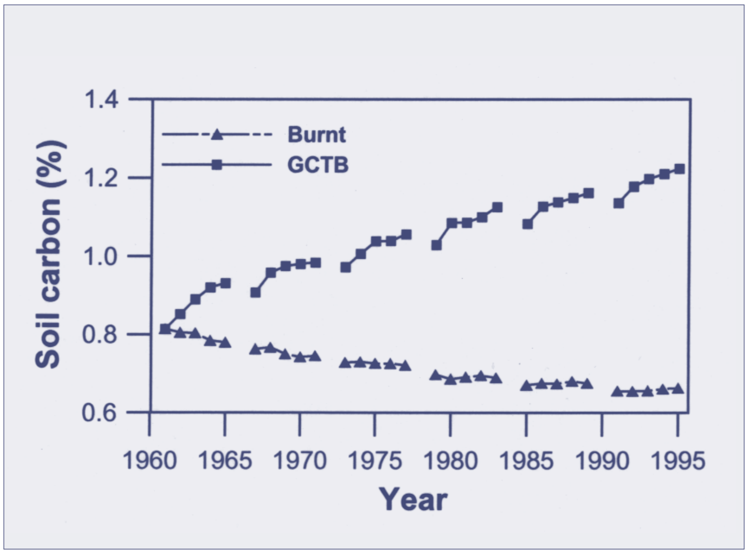

Figure 3. Simulated long-term changes in total soil carbon (0–0.2 m depth) in response to two trash management treatments. From Thorburn *et al.,* (1999).

Most trash management experiments have not yet continued long enough to be conclusive of the long-term effects. The longest experiment in Australia is that initiated by Wood (1986, 1991) on an alluvial silty soil at Abergowrie, west of Ingham, north Queensland. This experiment provided the data for the modelling studies of Vallis *et al.,* (1996) and Thorburn *et al.* (1999). The former modelling activity used the CENTURY SOM model (Parton *et al.* 1987) with a simple sugarcane crop routine, while the latter used APSIM (McCown *et al.,* 1996) with a more elaborate and better tested sugarcane module (Keating *et al.,* 1999) and comprehensive soil organic matter module (Probert *et al.,* 1998).

The conclusions from the two modelling studies were similar. Here we focus on the APSIM simulations for relevance to contemporary activity. Over 2 crop cycles (15 years) there were only very small effects on crop yield but a steady increase in the SOC in the 0–20 cm soil for the GCTB treatment compared with the conventional burnt system (Figure 2). A feature of the results, and of the modelled predictions, was that SOC responded very slowly to the retention of the residues. To explore this further, the model extended the comparison to a longer time period. The predictions suggest that over a time scale of 35 years, SOC under the conventional burnt system will have declined and that under GCTB will still be increasing (Figure 3). At this site the difference between the two systems is predicted to increase to at least 0.6%C (0–20 cm), but only over long time frames (> 30 years).

Potential C Sequestration

Sugarcane systems are sequestering C as a result of the adoption of GCTB. Based on the simulations for the one site in north Queensland (Figure 3), it seems possible that the difference may ultimately reach at least 0.6% C in the 0–20 cm layer. Assuming a bulk density of 1g/cm^3, this would amount to an additional 12 t/ha of C in the GCTB system compared with the conventional burnt system. In much of the industry, the time since adoption of this practice has not yet been long enough for the systems to come to a steady state with respect to the new management. Thus, C sequestration is still occurring, although the amount that could be sequestered in future is difficult to estimate from current knowledge.

Two points need to be stressed in relation to extrapolation of the findings of the Abergowrie experiment. First there are good reasons (based on understanding of SOC dynamics) for expecting the effects of adoption of GCTB to vary with the SOC content when the changed management is imposed. The second point is whether the Abergowrie experiment is typical. Figure 1 suggests that the short-term effects on SOC in the uppermost soil layers has been greater at other sites.

From the point of view of estimating the 1990 baseline for carbon accounting purposes, it would be necessary to establish the extent and length of time since adoption of GCTB at that time.

If the rest of the industry moved to GCTB, it seems likely that additional C could be sequestered. However there may be substantive reasons why the practice will not extend to the whole industry.

What other options are there?

For the most part the sugarcane crop enjoys satisfactory nutrition. Best prospects for growing bigger crops would seem to come from better water management. Poor drainage is known to be a factor that limits yield in the Herbert District and probably in other northern regions. South of Townsville, greater and more efficient use of irrigation could increase yields (Inman-Bambar *et al.,* 1999). Returns of C to soil would be expected to increase with increased yield.

Whilst improved drainage would result in higher yield, the effects might not be all positive in terms of C sequestration. Many of the soils that could benefit from better drainage are humic gleys that have high SOC because of the poor drainage. Draining such soils will lead to C losses.

Use of a break crop (such as a legume for green manure) following plough-out and before re-planting has attractions for disease control and improving soil structure and is the subject of current research. Any contribution to sequestration of C is likely to be quite small because the short time available for growing the break crop (maybe 4 months in the full rotation of 6 years) will limit the biomass that could be produced.

Studies are also being made of the potential of various legumes as seed crops with larger inputs, 'best' management, and cropping at more regular intervals in the sugarcane cycle (ie not just as low input, short term manure crops) (Allan Garside, personal communication).

Other greenhouse gases

The sugarcane industry is a major user of N fertiliser. In 1997, N inputs were in the vicinity of 80,000 tonnes of N/ha/year (Keating *et al.,* 1997). The nature of the climate with intense rainfall events results in periods when soils are anaerobic. Denitrification and emission of N_2O do occur, most notably on heavy textured soils. Although Weier (1998) attempted to extrapolate short-term point measurements of N_2O emissions to the entire sugarcane industry, the highly site specific and episodic nature of denitrification events suggests such extrapolations should be treated with caution.

Improving efficiency of N fertiliser use and better management of soil water, perhaps using fertigation, should be capable of reducing emission of N_2O.

Burning cane results in emissions of CH_4. Weier (1998) estimated emissions of 6.7 kt/y CH_4-C for the whole sugar industry. Soils can also be sinks for atmospheric CH_4. The experimental data of Weier (1999) show periods of both consumption and emission occurring for trash blanketed soil. However the magnitude of the CH_4 consumption was much smaller than had been measured previously and which was the basis of the estimate of a sink of 34 kt/y of CH_4-C for the industry (Weier, 1998). As for the N_2O emissions, the fluxes of CH_4 are very uncertain.

Conversion of the whole industry to GCTB would prevent emissions of CH_4 arising from burning. However there would be increases in denitrification and emission of N_2O (by ~30 %) in a GCTB system (Weier *et al.*, 1998).

DRYLAND CROPPING SYSTEMS

The so-called northern grains region stretches from Dubbo in northern NSW to Clermont in Central Queensland. The climate across this region is semi-arid with extremely high season-to-season variability in annual rainfall. As one moves south the distribution of rainfall changes from being strongly summer dominant to a more even split between summer and winter. Cropping is largely possible because of the high water holding capacity of the deep clay soils which enable crops to tolerate the extended periods between rainfall events; this is particularly so in the northern part of the region.

The pattern of rainfall permits growing of both summer and winter crops of cereals (sorghum, wheat and barley), pulses, oilseeds and cotton. The introduction of dryland cotton is a relatively recent change to the cropping systems. It is estimated that the total cropping area of the region is about 6M ha, though not all of this is cropped every year.

The history of cropping in the region has been the exploitation of soils that were initially highly fertile. Without inputs of any nutrients it was possible to grow high protein wheat. However over time there has been a decline in soil organic matter and in the soils' ability to supply N for crops (Dalal and Mayer, 1986). As well as nutrient mining, the soils were very susceptible to erosion. Contour banks and, more recently, conservation tillage with retention of stubbles to provide surface cover have largely overcome the threat from erosion. Expansion of the cropping area has been towards the west onto land that is more marginal in terms of rainfall and of lower fertility that will suffer fertility decline even more rapidly than the better soils.

Several long-term experiments have studied the effect of stubble management, tillage, fertiliser, and crop rotations on crop yields along with changes in SOC and/or Soil Organic Nitrogen (SON). SOC and SON usually respond in a similar manner, with the C:N ratio changing little over time or in response to treatments. A limitation of the experimentation is that it has tended to ignore possible effects on SOC in subsoils. In most studies measurements have been for the surface layer only (often 0–10 cm).

At Hermitage, near Warwick, Qld in a winter cropping system on a vertisol, SOC declined over more than 20 years for all combinations of tillage, residue management, and fertiliser input. The dominant effect was the retention of stubble which slowed the run down of SOC; smaller effects were obtained from use of N fertiliser. Tillage (conventional vs zero till) had no effect on total SOC or total N in the 0–100 mm layer, though there was some stratification within this layer (Dalal *et al.*, 1991).

Broadly similar results were reported by Heenan *et al.* (1995) in an experiment over 14 years on a red earth at Wagga Wagga, NSW where the initial SOC was high following many years of sub-clover based pasture. Decreases in SOC in the 0–10 cm layer occurred for lupin-wheat and continuous wheat rotations, with both stubble retention and direct drilling reducing losses compared with conventional cultivation and burning. In the sub-clover-wheat rotation SOC was maintained at close to the initial content.

Of particular note, neither of these experiments showed any evidence that under the continuous cropping systems the SOC had reached a steady state within the experimental period.

The findings were different on a red-brown earth at Condobolin in western NSW (Fettell and Gill, 1995). In this low rainfall environment, direct drilling and stubble retention with continuous wheat for 15 years had no significant effect on SOC or total N, but SOC was higher (and crop growth also increased) where N fertiliser was applied.

The Soil Restoration Experiment at Warra, Qld has not run as long as the other experiments. Dalal *et al.* (1995) reported data for 1986 to 1994. Changes in SOC and SON in the surface 0–10 cm layer for the continuous wheat and two year rotations of wheat and legumes (chickpea, medic, lucerne) were small. The only treatment that consistently increased SOC (and N) was the 4 year grass-legume ley. This treatment was able to raise SOC from ~0.7 to ~0.8% during the ley; upon return to cropping the SOC content declined towards that measured in the other treatments.

The data from the Hermitage experiment were used by Probert *et al.* (1995) to test the ability of the CENTURY and APSIM models to represent the behaviour of the system. Both models predicted the declines in SOC, and the effects of the treatments (stubble management, N fertiliser) that were in satisfactory agreement with the observations.

To date, the APSIM modelling framework has been directed more towards productivity issues (including the dominant resource drivers of water and mineral N) than SOC. The Warra Experiment has been a key data set for establishing that APSIM is capable of realistically representing yields and soil water and nitrate-N for a cropping system over a sequence of crops. This would not be possible unless the model was performing sensibly in terms of the mineralisation of soil organic matter and the immobilisation of mineral N when crop residues with high C:N ratio decompose. The soil C predicted by APSIM for some of the Warra treatments is shown in Figure 4. There is good agreement between the simulation and the experimental results in that changes in SOC are small for these cropping systems.

The degradation of SOC is predicted to be most rapid through 1991–92. This results from the enforced long fallow arising from the lack of a planting rain in 1991. A similar effect was highlighted in the simulation of the Hermitage Experiment (Probert *et al.,* 1995). There is a considerable difference in the predictions of the magnitude of the decline in SOC at the two sites. At Warra the decrease in SOC is less than at Hermitage (or Wagga Wagga) reflecting the lower initial SOC at Warra where the soil had a prior history of cropping.

Options for increasing C sequestration

Experimentally it has been shown that retention of stubble has the largest effect on SOC. Throughout the region this is already normal practice in order to control erosion.

The "bigger crop" option has some prospects. Where SOC has declined to the extent that wheat yields and quality are limited by N supply, there are prospects for increasing yields and return of residues through fertiliser or biologically fixed N. The experimental results suggest that increases in SOC from use of fertiliser N or short legume-cereal rotations are not going to be large.

Better prospects are offered by the "more crops" option. Particularly in the southern part of the region dryland salinity is of major concern. Increased water use efficiency and reduction in the deep drainage component of the soil water balance can be achieved by double cropping. Where two crops can be grown per year, it is to be expected that the greater returns of crop residues would result in increased SOC. Thus this is a situation where there are win-win opportunities (for greater outputs of crop produce, less drainage and higher C sequestration). Current models are well-suited for evaluating how often double cropping would have been possible based on the historical weather records (see for example Keating *et al.,* 1995; Paydar *et al.,* 1999). However this too is currently recommended as best practice to maximise effectiveness of water use and it is uncertain what scope there may be to increase its adoption.

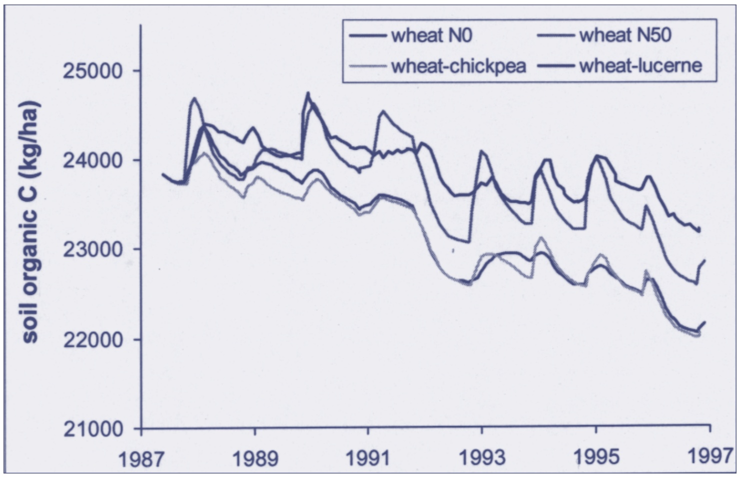

Figure 4. Simulated change in SOC in the 0–20 cm layer for selected treatments of the Warra Experiment. The continuous wheat treatments (N0 and N50) are for conventional tillage. The wheat-lucerne treatment refers to the two year rotations.

Even better prospects for sequestering C come from introduction of pastures. The Warra experiment shows clearly that this is possible, but we are unaware of any study that provides information on what the potential C sink might be under permanent pasture. There has been a long history of interest (mainly by scientists) in the use of pasture leys for improving the sustainability of farming systems. However its adoption by the industry has been slow even by those involved in 'mixed farming' (Weston and Doughton, 2000). Reasons no doubt include the management complexity of ley systems and economics. McCown (1993) has pointed out that shifts between pastures and cropping have invariably been rational based on the economic returns of the alternative systems.

From the standpoint of sequestration of C, a pasture ley in rotation with cropping will result in a fluctuating SOC store, building up under the ley and then declining under cropping. A more permanent increase in SOC could only arise from conversion of cropland to pastures.

Although "pastures" may suggest a lower input system in terms of nutrients, they will be a sink for nutrients if significant amounts of C are to be sequestered. Formation of soil organic matter containing 1 tonne of C will also require ~100 kg N, ~10 kg P and ~10 kg S. Whilst the N may be fixed by a legume component in the pastures, extra P and S may have to be supplied as fertilisers (and positive effects of C sequestration discounted by negative effects associated with fertiliser manufacture and distribution).

Other greenhouse gases

The productivity of all cropping systems is dependent on nitrogen. Increasing productivity through more crops and especially bigger crops implies there would need to be greater amounts of N in the system. Climatic variability in tropical areas, particularly high rainfall events, means high risk of water-logged, anaerobic conditions. When these coincide with high nitrate-N concentrations in soil, denitrification will result in emission of N_2O.

Systems that depend on N fixed by legumes can be just as susceptible to denitrification losses as those using fertiliser. Because denitrification also requires a carbon energy source, potential losses after a legume ley can be particularly high if anaerobic conditions follow soon after a period of rapid mineralisation (Wayne Strong, personal communication).

Conversion of cropping land to pastures that are used for animal production would increase the emissions of CH_4 from livestock.

IRRIGATED COTTON SYSTEMS

The modern cotton industry in Australia commenced in the 1960's. Principally an irrigated crop, it is grown in the Namoi, Macintyre, Gwydir, Macquarie River valleys of northern NSW and at St George, Emerald and on the Darling Downs in Queensland. Because of the good economics of the crop (compared with other dryland crops) in recent years there has been an increase in dryland cotton. In good years the dryland crop has been up to 20% of the total planted area, but it amounts to <10% of the total production. The total area of irrigated cotton was ~350,000 ha in 1997–98 (Cotton Yearbook, 1998).

Irrigated cotton is grown predominantly on cracking clay soils. It is a crop that is difficult to grow according to good conservation tillage practices. Leaves that are shed during defoliation decompose readily, but the bulk of the residues are woody so do not decompose readily; control of pests and disease is of major concern; surface trash and flood irrigation are not compatible. Thus normal practice used to be to pull or slash, and then burn the crop residues. This is still widely practiced, though reduced tillage through the use of permanent beds has become common. Under these conditions, input of C in crop residues must be small.

Another difficulty arising from flood irrigation is the deterioration of soil structure. Restoration of structure is best achieved by drying/wetting cycles. Rotation systems, especially with winter cereals (wheat), provides several possible benefits including:

- improved soil structure and thus better infiltration and water use efficiency by subsequent crops,
- disease control by increasing the time for pathogen inoculum in the soil or on residues to decline,
- prospects for better weed control by permitting wider spectrum of chemicals to be used, thus reducing risk of weeds developing resistance,
- where residues from the cereal are retained it is likely that higher soil organic matter contents can be maintained.

However within a cotton growing system, there are few prospects for increasing the intensity of cropping. Typically wheat grown after cotton will result in a long fallow back to the next cotton crop.

Data on the long-term effects of irrigated cotton on SOC are sparse. An experiment at the Australian Cotton Research Institute at Narrabri compared three experimental treatments between 1985 and 1993 (Nilantha Hulugalle, personal communication). The treatments were continuous cotton with either intensive tillage or minimum tillage and a cotton-wheat rotation (minimum till cotton; no-tillage wheat). For all treatments the crop residues were slashed and shredded after harvest and retained in situ. Regressions of SOC in the 0–0.6 m profile against time had negative slopes for all three treatments. The intensively cultivated cotton had the greatest decline in SOC. The cotton-wheat rotation tended to have the highest SOC. Averaged over the three treatments, the loss of SOC (0–0.6m) was 2.1 t/ha/y of C.

In several short-term (<5 year), on-farm experiments, slopes of the regressions of SOC (0–0.6m) on time were also negative for all treatments, averaging 3.3 t/ha/y (Hulugalle, personal communication). No differences could be established between continuous cotton or cotton rotations with cereals or legumes.

These rates of loss of SOC for irrigated cotton are much higher than measured in dryland cereal systems. For example, Dalal *et al.* (1991) measured a rate of loss of total soil N in the 0–0.1m layer (though most of the change occurred in the 0–0.05m layer) of ~25 kg N/ha/y. With an assumed C:N ratio of 12, this would equate to ~0.3 t/ha/y of C. The wetter soils in the irrigated system is one reason why rates of loss of SOC would be expected to be higher.

However there are other reports where loss of SOC are not as high. In an experiment, carried out on a soil that had previously supported cotton crops grown under minimum tillage, the trend in SOC (0–0.3m) over 3 years was an increase of 1.6 t/ha/y when stubble was incorporated compared with an increase of 0.6 t/ha/y when stubble was burnt (Conteh *et al.,* 1998).

Other greenhouse gases

Efficiency of use of fertiliser N in irrigated cotton is typically low. Denitrification is the dominant process leading to loss of N, with losses commonly exceeding 50% of the applied N (Freney *et al.,* 1993). Factors contributing to the anaerobic environment are the reliance on flood irrigation and the poor soil structure of the heavy clay soils, especially where compaction has occurred as a result of tillage and trafficking under less than ideal soil conditions.

There are prospects for reducing denitrification losses (and emissions of N_2O) through use of chemicals that inhibit nitrification and/or suppress microbial reduction of nitrate under anaerobic conditions. Recent laboratory studies (Rochester and Constable, 2000) indicate that the improvement in N fertiliser recovery using etridiazole is predominantly by inhibiting nitrification with little direct effect in suppression of denitrification. Since reduction of N loss improves fertiliser use and can increase cotton lint yield there is potential for a win-win situation in terms of lower emissions of N_2O and better economics of fertiliser use.

Management Options for C Sequestration with Alternative Systems

The "different crop" option provides the best prospects for increasing C sequestration in tropical cropping systems. In principle, two aspects of the C cycle can be modified, namely higher Net Primary Production (NPP) and a smaller amount of fixed C removed as produce.

For the dryland cropping systems, the possible role of pasture (and especially legume) leys, were mentioned above. Whilst such systems are attractive as being more sustainable because of their contribution of N to subsequent crops as well as improving soil structure and infiltration, their adoption by the industry has been slow.

To be really effective in increasing SOC, cropping lands need to be converted to pasture permanently otherwise the sink for C under pasture becomes a source when the land is returned to cropping.

Introduction of trees to cropping lands results in the creation of a new, potentially large, C pool, namely the biomass of the trees. Options would cover the spectrum from establishing plantation forestry through to scattered trees (agroforestry).

The introduction of trees is also an option that is seen as having merit in terms of reducing deep drainage and ameliorating the dryland salinity problem. Thus this too offers a potential win-win situation. However at a density and geometry of trees appropriate for reducing drainage it seems probable that there would be some competition for limiting resources (water and/or nutrients) between the trees and adjacent cropping lands in an agroforestry system.

Historically introduction of forests has occurred on the most marginal agricultural land. It seems unlikely that a tree scenario could be economically attractive in either the irrigated cotton or sugarcane systems. Booth and Jovanovic (1991) assessed land suitable for commercially viable tree plantations. One of the most important criteria is rainfall. Over 1000 mm was assessed as highly suitable, 600–1000 mm as moderately suitable. On this basis most of the dryland cropping region would be judged as not being highly suited for development of commercial tree plantation. However it is in the 600–800 mm rainfall region that there is need for control of deep drainage and where there may be scope for using trees.

Measurement and Verification Issues

Accurate measurement and verification of C sequestration in cropping systems will be extremely difficult to achieve. The major difficulty is that the outcome of imposing some alternative management depends on the current SOC content, which in turn depends on past land use. Thus effects will vary on a paddock by paddock basis. Obtaining a true picture of the SOC content of the cropping area would be very demanding.

Approaches to estimating soil carbon changes have been suggested based on fractional change in the soil carbon store. However there is good reason to expect that the fractional change (and in some cases even whether the change is positive or negative) will depend on the current SOC content. The approach is likely to be rather imprecise unless it can be linked with good information on SOC.

Models of the plant-soil-atmosphere that are sensitive to issues such as residue management, tillage etc need to operate at a scale that is incompatible with larger scale resource issues (such as emissions of greenhouse gases, drainage, etc). APSIM currently has modules of crops and soil organic matter that make it well-suited for exploring effects of alternative cropping systems on changes in soil C. These capabilities are suitable for evaluating the effects on soil C of various rotations of arable crops and issues such as double cropping. Development work is in progress that will result in modules that can simulate grasslands and trees.

An attraction of simulation is that it provides a means of extrapolation to other farming systems, soils, and climates. But this only becomes possible to the extent that the model is credible. Validation of APSIM has focussed more on its ability to predict plant growth than on SOC. This is mainly because there are few suitable datasets that have the full range of plant, soil and climate data. To test the SOC aspects of the model thoroughly there is need for long-term data. A strength of APSIM is its widespread use and testing against available plant and soil data across a wide variety of environment and soils. For those experiments where changes in SOC have been measured, covering the range from sugarcane to dryland cropping on vertisols, model performance has been shown to be satisfactory, but there is need for the testing to be applied to a wider range of environments and soils. Furthermore, the algorithms used in APSIM are very similar to those of many other models (such as Roth-C or CENTURY) which contributes to confidence in its use.

It should be stressed that the ability to predict the behaviour of alternative cropping systems for a given scenario does not deal with the over-arching problem of how to stratify the cropping area to cope with the existing SOC that may be variable from paddock to paddock.

Uncertainties and R&D Needs

Experimentation on the effects of management on SOC has largely ignored the subsoil. There are reports on how various treatments cause stratification of C within the 0–10 cm layer but rarely have measurements been made of the deeper soil. Thus there must be uncertainty about the total change in SOC that has occurred as a result of cropping, and also about the changes that occur when cropping management is changed. However the experimental data are consistent in that effects diminish with depth.

Calculation of total C in the soil profile requires data for both SOC (usually reported as gravimetric % of the dry soil) and bulk density. Bulk density is likely to have changed during cropping due to loss of soil structure that accompanies degradation of SOC. Management that increases SOC is likely to also cause changes in bulk density.

It has also been normal practice to only analyse the so-called fine earth fraction of a soil sample. Where unknown amounts of nodules or other hard fragments have been discarded from the whole soil there will be difficulties in using historical data for SOC.

Models of the dynamics of soil organic matter require information on the inputs of C derived from the vegetation. For annual crop systems, the above ground contribution is readily measured. However good data of the below ground system are lacking and there is generally poor understanding of carbon loss from roots. This becomes an even greater uncertainty for perennials were assumptions have to be made about the annual cycle of growth and death, and how roots respond to defoliation and grazing.

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Current and Future Carbon Storage in the Western Australian Wheat Belt

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Introduction

The Western Australian wheat belt occupies approximately 15 million hectares of cleared land in the 300–600mm rainfall zone of south-western Australia. The area is currently undergoing rapid change, largely in response to the expanding threat of secondary salinity. Restoring perennial vegetation, comprising both woody and herbaceous species, is an explicit target of The Salinity Strategy (Government of Western Australia, 2000). Specific targets include 3 million hectares of woody tree crops, incorporating 1 million hectares of oil mallees by 2015. Concurrently, the area expected to become saline is expected to increase to about 30% of the total area within the next 50 years under a 'do nothing' scenario, or about 20% with a reduction in recharge of 50%. A substantial proportion of this salt-affected area will be planted to saltbush or other salt-tolerant perennial vegetation. The combined effects of these changes could potentially have an impact on carbon sequestration both above and below ground.

In this paper, we estimate the magnitude of carbon storage under current land management strategies, using both estimates based on levels of dry matter production for above and below-ground carbon, and the Rothamsted carbon model (Jenkinson *et al.*, 1987) for below-ground carbon. We then compare these values with carbon storage under what we consider is a likely scenario (in terms of land management) in 10 years time. We pay particular attention to the possible role of herbaceous perennials as a carbon sink.

Land Use Classes

Various land uses were broadly classified into one of five classes: annual crops and pastures (conventional agriculture), herbaceous perennial pastures (eg lucerne); alley systems with woody perennials; blocks of woody perennial plantations; and saline areas. We assumed that the area of remnant vegetation would not change. Above and below ground carbon was estimated for each class as described below, and summarised in Table 1. Below-ground carbon was further broken down into two conceptual pools: a pool including fresh root material, which could change with different land use; and a more resistant pool, the size of which was independent of land use, at least in the short term.

ANNUAL CROPS AND PASTURES

Due to the seasonal nature of annual plant growth in the mediterranean-style climate of south-western Australia, above-ground dry matter (DM) production varies considerably throughout the year, reaching a maximum early in summer, and declining to a minimum early in winter. There is also considerable variation from year to year, depending on rainfall and other growing conditions. Given that the average wheat yield for Western Australia is approximately 2 t grain/ha, and assuming a harvest index of 0.4, the average maximum (late spring or early summer) above-ground dry matter value is of the order of 5 t DM/ha. Further assuming that carbon makes 40% of the dry matter, the maximum carbon storage above ground is approximately 2 t C/ha (Figure 1). A minimum stubble

Land Use	Above-ground C (t/ha)	Root C (t/ha)	Soil C (t/ha)
Annual Ag	1	0.6	19.4
Perennial Ag	1	1.0	19.4
Alleys	5	2.0	19.4
Plantations	40	15	19.4
Salt land	1.3	0.8	19.4

Table 1: Average above-ground and below-ground carbon storage (t/ha) for various land uses in the Western Australian wheatbelt.

cover of 2 t DM/ha (0.8 t C/ha) was recommended by Felton *et al.,* (1987), but sometimes minimum values can approach zero just before sowing in autumn, particularly in situations where crop stubble is burnt or heavily grazed. Using Figure 1, an average yearly figure of 1.0 t C/ha was used in our calculations.

For below-ground carbon, samples from the top 10 cm of 90 soils throughout the Western Australian wheatbelt gave a median carbon content of 1.0% (M. Wong, unpublished). 83% of samples were in the range 0.5–1.5% C. Using a figure of 1.0%, and assuming a soil bulk density of 1500 kg/m3, carbon in the top 10 cm of agricultural soils amounts to 15 t C/ha. Further assuming that 75% of total soil C resides in the top 10 cm (Jeff Baldock, CRCGA, personal communication), a value for total below ground C of 20 t C/ha was used. The 'root' pool was calculated assuming the proportion of fresh roots was equal to 30% of the maximum above-ground biomass (rough average of data presented by Dunin *et al.,* 1989; Gregory *et al.,* 1992; Crawford *et al.,* 1997), or an average of 0.6 t C/ha, and the independent pool consisted of the rest of the soil carbon, or 19.4 t C/ha. Dunin *et al.* (1989) also made the important observation that as much as 20% of the carbon assimilated by an annual crop was derived directly from decomposition of soil organic matter, rather than captured from the atmosphere.

Specific data from Moora and Wongan Hills shows that total soil carbon, to a depth of 1.0 m, was similar for native vegetation and long-term cropped areas (M. Wong, unpublished), suggesting that roots occupy a small proportion of the total soil organic pool under Western Australian conditions. Furthermore, these results also suggest that, under Western Australian conditions, major changes in land use might only have a small impact on soil carbon. This is supported by Hamblin and Tennant (cited by Hamblin, 1987), who showed that after 6 years of zero-till, compared with conventional cultivation, organic carbon only increased by about 0.1% in representative Western Australian soils. This is not surprising, given the characteristically low clay contents (usually less than 5%) of the majority of Western Australian surface soils (Tennant *et al.,* 1992). Soils with low clay contents generally have low organic matter contents because they have few sites within the soil offering physical protection to organic matter (Oades, 1995).

Given the area currently under annual agricultural production in south-western Australia, even small changes in soil organic carbon storage may lead to large accumulations in total carbon storage for the region. However, we see no evidence that farmers are making systematic changes to their annual farming systems (such as minimum tillage, stubble retention, etc) that would lead to such an increase.

HERBACEOUS PERENNIAL AGRICULTURAL VEGETATION

Herbaceous perennials, such as lucerne, usually differ slightly from annual crops and pastures in their seasonal patterns of above-ground dry matter production, producing more in summer and autumn, and less in winter and spring. However, their total annual production is similar, and so we have used the same figure for above-ground carbon as for the annuals.

Below ground, perennials tend to invest more resources in root production. Limited comparative data (Ward, unpublished) suggests that in a second year lucerne stand, total root dry

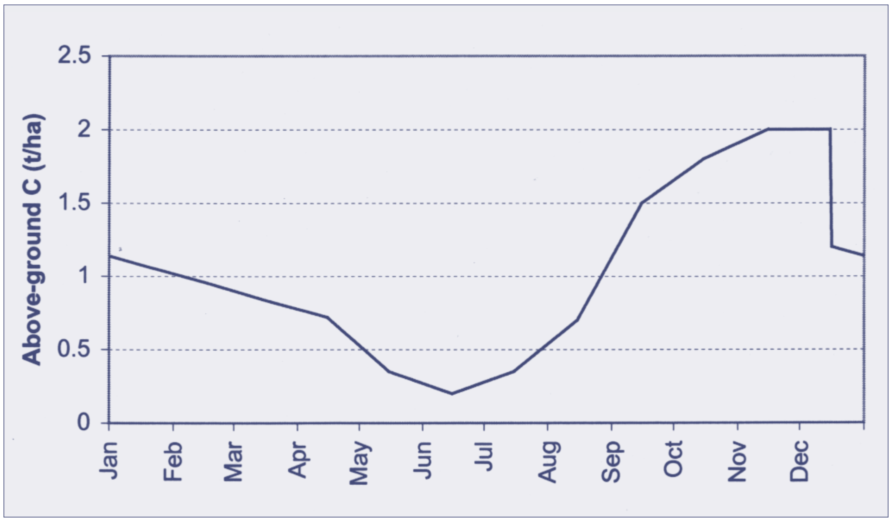

Figure 1: Average yearly cycle of carbon retained above-ground for annual crops in the Western Australian wheatbelt.

matter (including roots greater than 2 mm in diameter) to a depth of 2.0 m was approximately 1.7 times greater than for an annual pasture, giving a total root pool of 1.0 t C/ha. Because lucerne is being included in rotations largely at the expense of annual pastures within the cropping rotation (that is, not changing the overall crop:pasture ratio), we have assumed that lucerne will have no impact on the major soil carbon pool. However, if lucerne can store carbon at depths greater than traditional annual crops and pastures, as seems likely from water uptake evidence, there is a possibility that soils under lucerne may, over several phase rotations, tend towards slightly higher carbon values. This was supported by the Rothamsted carbon model, which predicted an increase in soil carbon (compared with annual cropping) of about 6%, which increased the total below-ground storage from 20 t C/ha to 21.2 t C/ha. Similarly, an increase in soil carbon from 1.0% to 1.1% (Hamblin, 1987) would increase the 'non-root' carbon pool from 19.4 t C/ha to approximately 21 t C/ha. This figure is also discussed in the "Current and Future" section.

WOODY ALLEY SYSTEMS

In this class, we include any woody perennial species grown as strips or alleys within a more traditional farming system. Species can include *Acacia saligna*, tagasaste (*Chamaecytisus proliferus*), various eucalypts including oil mallees (such as *Eucalyptus kochii, E. horistes, E. radiata, and E. angustissima*), and sometimes Maritime pine (*Pinus pinaster*). The woody species typically occupies about 10% of the landscape (Ted Lefroy, personal communication), and so values of above-ground and below-ground carbon were calculated from the sum of 90% of annual and 10% of woody plantations.

WOODY PLANTATIONS

Climax communities of remnant mallee vegetation in the 300–500 mm rainfall zone contain very roughly about 50 t/ha dry matter, or about 20 t/ha above-ground carbon. Plantations, due to their more intensive management and fertiliser applications, may be considerably more productive. For example, plantations of Maritime pine could store as much as 100 t C/ha above-ground and a further 10–15 t C/ha below ground 10 years after establishment (Shea *et al.*, 1998). On the other hand, oil mallees may only store 3 t C/ha above ground (due to frequent harvests), but as much as 28 t C/ha below ground (Shea *et al.*, 1998). Hassall & Associates (1999) estimated annual carbon sequestration of 10 year old plantations in the 400–600 mm rainfall zone at about 5 t C/ha. The Rothamsted carbon model predicted total soil carbon under an average plantation at about 88% higher than an annual system, or approximately 38 t C/ha. As an average for broadacre woody areas, we have taken 40 t/ha carbon above ground, and 34.4 t/ha (consisting of 15 t/ha roots and 19.4 t/ha soil organic matter, as for the agricultural communities) below ground.

SALT-AFFECTED LAND

Salt-affected land in Western Australia is often planted to salt-tolerant perennial vegetation, such as saltbush (*Atriplex* species). The low scrubby vegetation alone can produce more than 2 t DM/ha (Warren *et al.*, 1995), or 0.8 t C/ha. When combined with the production from salt-tolerant annuals, which we assume is half the level calculated for agricultural annuals as described above, the total carbon store could be of the order of 1.3 t C/ha.

No figures are available for carbon storage below ground under saline conditions. However, in some saline areas, saline-sulfidic soils can develop, partly due to an accumulation of soil organic matter (Fitzpatrick *et al.*, 1996), due to anaerobic soil conditions. For our calculations, we have assumed that saline soils under sparse salt-tolerant perennial vegetation would possess root carbon levels half way between the levels for annual and herbaceous perennial vegetation. In the long term, organic matter may tend to accumulate under these conditions.

ANIMAL PRODUCTION

Current indications are that livestock numbers in the wheatbelt of Western Australia will remain relatively constant at between 20 and 30 million DSE. The possible expansion of woody plantations, reducing the area for livestock, will probably be balanced by increasing the quality of pastures (particularly herbaceous perennials), which will increase the carrying capacity of these areas.

CURRENT AND FUTURE SITUATION

The approximate area currently occupied for each land use class, and an estimate of areas occupied in ten years, is summarised in Table 2.

Of the land under annual agriculture, approximately 6.4 m ha is cropped, and the remaining land is pasture (Anon, 1999). For perennial agriculture, just over 100 000 ha of lucerne has been sown in the last three years (Lisa Blacklow, personal communication), and given recent increases of seed sales (Julie Newman, personal communication), a target of 1 m ha within 10 years seems achievable. We have assumed that this increase in area (as for the increases in alleys, plantations and saline

Land Use	Current area (Mha)	Area in 10 years (Mha)
Annual Ag	12.7	10
Perennial Ag	0.1	1
Alleys	0.1	0.5
Plantations	0.1	0.5
Salt land	2	3

Table 2: Estimates of current areas and areas in 2010 occupied by various land uses in the Western Australian wheatbelt.

Land Use	2000 above-ground C (Mt)	2000 root C (Mt)	2010 above-ground C (Mt)	2010 root C (Mt)
Annual Ag	12.7	7.6	10.0	6.0
Perennial Ag	0.1	0.1	1.0	1.0
Alleys	0.5	0.2	2.5	1.0
Plantations	4.0	1.5	20.0	7.5
Salt land	2.6	1.6	3.9	2.4
Total	19.9	11.0	37.4	17.9

Table 3: Current and 2010 projections for total carbon stored above ground and in roots for various land uses in the Western Australian wheatbelt.

land) occurs at the expense of area under annual agriculture. For alleys and plantations, current and future areas are broadly in line with estimates by Shea *et al.* (1998) and Anon (2000). Saline land estimates were taken from Ferdowsian *et al.* (1996).

Total carbon storages (Table 3) show a difference, due to change in land use, of 6.9 Mt of root carbon, and 17.5 Mt of above-ground carbon, for the entire wheatbelt area. The anticipated expansion of plantations, from 0.1 million hectares to 0.5 million hectares, provided most of the benefit, particularly above ground. Assuming that herbaceous perennials, alleys, plantations and salt land increase in area at the expense of annual agriculture, total net changes are 0.4, 2.2, 22.4 and 0.5 Mt respectively.

The impact of the expected net increase in the area of herbaceous perennials was minor, amounting to less than 2 Mt of carbon for the entire area. Even allowing non-root soil carbon to increase from 19.4 tC/ha to 21 tC/ha (as discussed above) only increases the total carbon store to 3.4 Mt in 2010.

Conclusions

By the year 2010, the agricultural regions of Western Australia will sequester more carbon than they currently do, largely due to increased woody plantations and alley systems. Herbaceous perennial vegetation is unlikely to have much impact, although there are many facets, especially in terms of root growth, where current knowledge is minimal. The effect of expanding areas of saline land on total carbon storage, particularly below ground, is unclear, and deserves further research.

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Agricultural Management Practices

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Slide 1

Article 3.4

Agricultural management practices

- To be of any value, soil C must be considered.
- The US is pushing hard for the inclusion of agriculture.
- Claims of up to 5 Gt C sequestered over the next 20 years.
- 75% of this will be as soil C through conservation tillage and residue management and adoption of improved cropping systems.

CSIRO LAND and WATER

Slide 2

Article 3.4

Agricultural management practices

- In Australia, the potential for C sequestration is far less.
- If all steps that could be taken to sequester C were implemented, a maximum potential of about 65 MtC/y would be achieved.
- Realistically, around 3-5 MtC/y for arable land and 13-15 MtC/y for rangelands could be achieved

CSIRO LAND and WATER

Slide 3

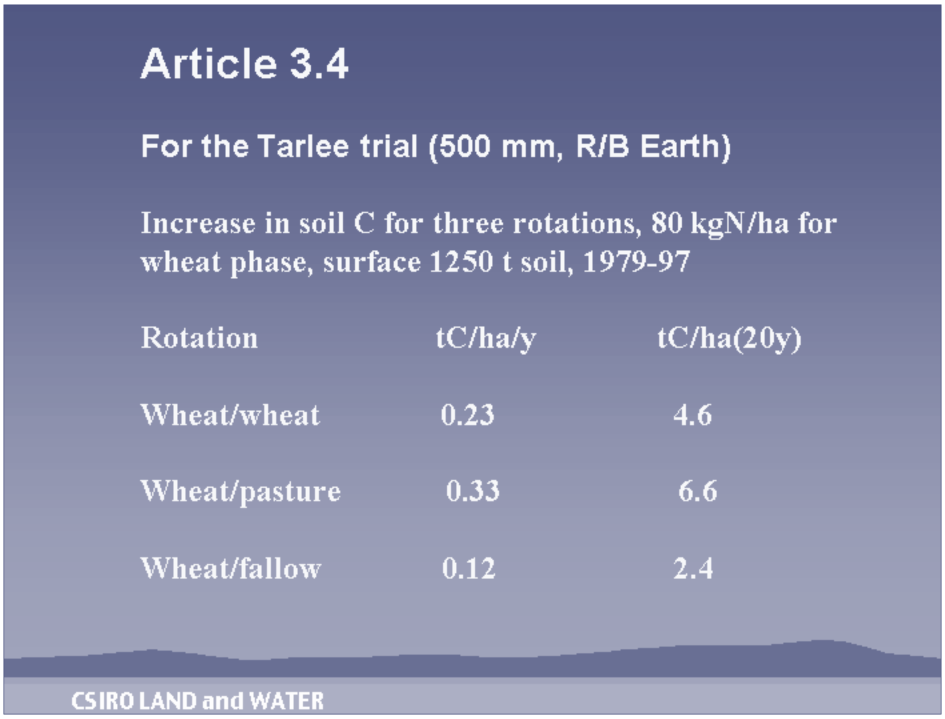
Article 3.4

Important factors are

- Climate
- Input (quantity and quality)
- Fallowing
- Initial soil C and pool structure
- Soil type
- Tillage?

CSIRO LAND and WATER

Slide 4



Article 3.4

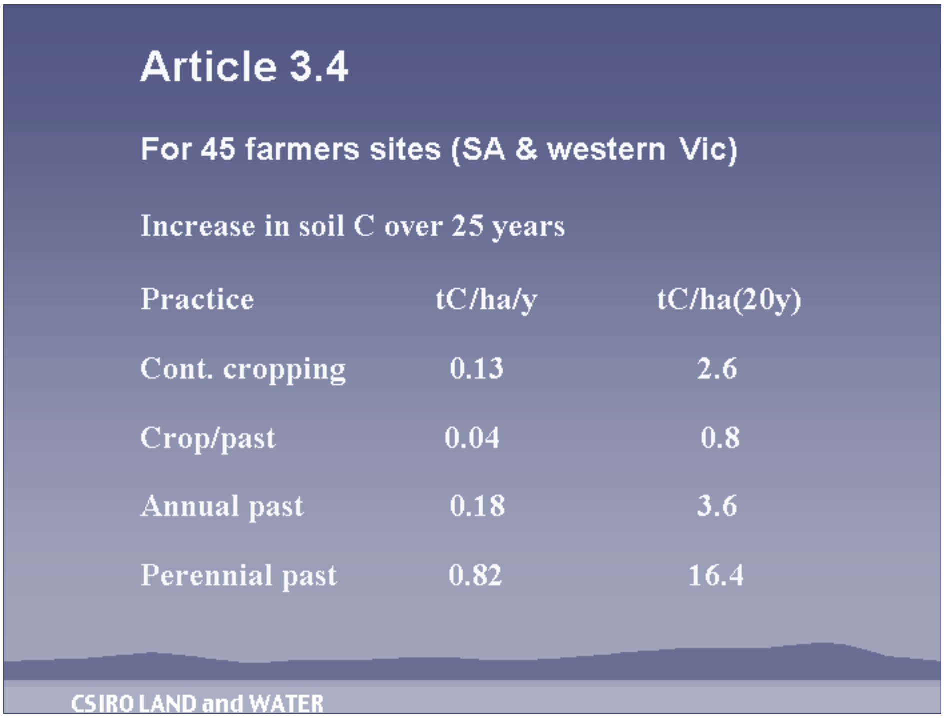
For the Tarlee trial (500 mm, R/B Earth)

Increase in soil C for three rotations, 80 kgN/ha for wheat phase, surface 1250 t soil, 1979-97

Rotation	tC/ha/y	tC/ha(20y)
Wheat/wheat	0.23	4.6
Wheat/pasture	0.33	6.6
Wheat/fallow	0.12	2.4

CSIRO LAND and WATER

Slide 5



Article 3.4

For 45 farmers sites (SA & western Vic)

Increase in soil C over 25 years

Practice	tC/ha/y	tC/ha(20y)
Cont. cropping	0.13	2.6
Crop/past	0.04	0.8
Annual past	0.18	3.6
Perennial past	0.82	16.4

CSIRO LAND and WATER