Long-term Nutrient Management

Summary and key findings on Long Term Nutrient Management

from a workshop held in

Adelaide
August 2007

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Nutrient Management Systems
healthy soils for sustainable farms
GRDC

Summary and Key findings from a workshop on *Long Term Nutrient Management* in Southern Australia

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Summary and Key findings from a workshop on *Long Term Nutrient Management* in Southern Australia

1. Introduction

A workshop on Long-term Fertiliser Use was held in March 2005 in Toowoomba, and in June 2007, a workshop on Long-term Nutrient Management in Adelaide reviewed a number of long-term trials conducted in Southern Australia. This document provides a summary of the Adelaide workshop and key findings from long-term trials in Eastern Australia.

The aim the recent workshop on *Long-term Nutrient Management* was to examine the key principles and information on the long-term management of soils and soil fertility by reviewing a number of long-term nutrient and agronomic practice trials in southern Australia.

The premise is that management strategies used for nutrients and other agronomic practices may change when we take a long-term focus. This paper will examine the implications of decisions about nutrient management with respect to long-term soil health, organic matter, carbon sequestration, and sustainability.

Some of the questions which arise when we consider nutrient management over a long period are:

1. What are the changes in soil fertility and nutrient balance over time with different cropping and nutrient management treatments?
2. What is the efficiency of fertiliser use and how does nutrient application relate to crop removal over the long term?
3. What is the effect of nutrient management and cropping systems on soil organic matter, soil health, WUE and productivity?
4. What interactions arise between nutrient management, cropping systems and other impacts, such as root disease or soil acidification?
5. Can farmers build soil carbon and reduce carbon dioxide emissions?

2. Short vs Long-term approaches to nutrient management

It is common for farmers, with help from agronomists, to make decisions for the next crop on their whole farm, on the basis of soil tests taken on a paddock or two.

This process has significant potential for errors including:

1. Sampling is prone to error with large variations in fertility across a paddock.
2. Sampling 0-10cm ignores soil nutrient supply below this layer.
3. Seasonal factors may affect availability of nutrients, particularly where the surface is dry for much of the season.
4. Nitrogen mineralization after sampling and during crop growth may vary according to the seasonal rainfall.
5. Soil tests for P and K do not account for movement between soluble and insoluble pools

The large errors which emerge from soil test recommendations is one reason farmers do not have a lot of confidence in soil tests and do not make greater use of them.

Soil testing is generally a short-term approach to nutrient management. Other approaches to soil nutrient management are possible, including fertiliser application according to nutrient removal over time and/or the fine tuning of fertiliser application in response to fertiliser trials measured by yield maps.

The role of soil testing can be changed to a monitoring role, to keep a check on changes soil carbon and fertility. A rigorous approach to soil testing and record keeping is necessary for this to be successful, with good paddock sampling and GPS referencing of sampling sites to enable tests to be taken in the same location several years later.

Farmers and agronomists are increasingly looking the longer term and asking such questions, such as those listed above. They are becoming increasingly concerned about nutrient balance, oil carbon over the long-term, fertiliser efficiency and soil health.

3. Soil Health, Organic matter and Greenhouse gas emissions

Greenhouse gas emissions and their effects on climate change are a contemporary issue, with important linkages to soil health and organic matter. The agricultural sector, according to the Australian Greenhouse office, is an important contributor to greenhouse gas emissions with an annual output equivalent to 88 million tonnes of carbon dioxide, representing 16% of total greenhouse gas emissions in Australia.

Agriculture is the source of more than 75% of Australia's nitrous oxide emissions, according to the Australian Greenhouse Office. Nitrous oxide levels in the atmosphere are minute compared with carbon dioxide, but the gas is estimated to have an effect on global warming some 310 times that of carbon dioxide. Soil management practices which impact on nitrous oxide emissions are therefore relevant to a general aim of reducing agriculture's greenhouse gas emissions.

Agriculture and land use change to faciliate farming, has contributed a significant amount of the additional greenhouse gases in the atmosphere. It has the opportunity to significantly reduce greenhouse gas output and make a major impact on overall reductions in greenhouse gas emissions. At the same time, most of the practices involved in reducing greenhouse gas emissions are likely to improve soil health and productivity and so is a win-win situation worthy of significant attention.

The clearing of farming land over the last four hundred years has released large quantities of carbon dioxide into the atmosphere. This release and the subsequent decline in organic matter and loss of carbon by other means, has been estimated (Lal 2004) to have contributed more carbon dioxide to the atmosphere, around 456 gigatons (Gt), than the 270 Gt estimated output from fossil fuel combustion since 1850. See table 1.

Table 1: Loss of carbon from farming land

Source	Carbon emission (Gt)
Pre-industrial crop lands	320
Post Industrial (1850-2000)	
- land use conversion	78
- soil erosion	26
- mineralisation of OM	52
Total loss from farm land conversion and farming	**476**
Fossil fuel use since 1850	**270**

Source: Lal 2004

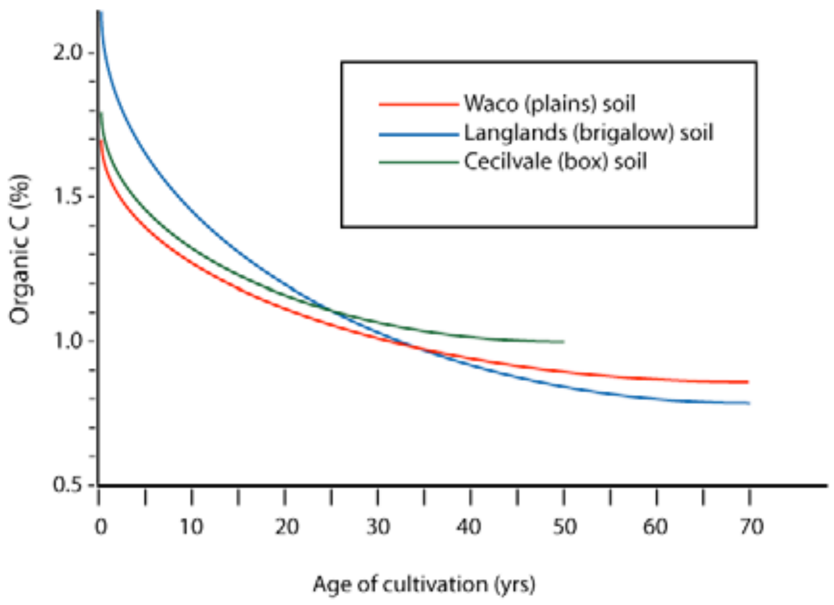
There is significant potential to reverse the decline of soil carbon according to Lal. The global soil Carbon pool of around 2500 Gt is 3.3 times the size of the atmospheric pool of 760Gt and the carbon sink capacity is around half of the historic carbon loss of 42 to 78 Gt. Farming land has the potential to offset fossil fuel emissions by storing 0.8 gigatons (Gt) of carbon per year, or around 10% of global fossil-fuel emissions.

At the same time this will help achieve the 50% increase in crop yields required between now and 2050 to feed the world. An increase of 1 tonne of soil carbon/ha is estimated by Lal to increase crop yield by 20-40 kg/ha. Lal says the increase in crop yield can be much higher than this on degraded soils where water intake is improved by increasing organic matter.

Decline in Soil Organic Matter has a cost

Many agricultural soils in Australia have lost a significant amount of carbon since they were first cultivated.

Figure 1: Decline in Organic Matter with cultivation



Redrawn from Dalal and Probert 1997

Data from paired sites has been used by Dalal to show the rundown of soils in southern Queensland amounts to around 40 tonnes of carbon per hectare over 60 years of cropping (See figure 1). Associated with this loss of organic matter is a reduction in soil nitrogen and other nutrients.

Losses of carbon in southern soils, as measured in long-term trials, have not been as severe, but most of these trials have started from a low soil carbon base after many years of cultivation. Soil carbon is discussed later in chapter 5.

The loss of nutrients and carbon has a cost. Based on data from comparisons between cultivation of different ages, Dalal (2005) has estimated that the total value of lost carbon and nutrients in a brigalow soil is, at current prices, is $6,320/ha over 60 years with an annual cost of $105 per year (Table 2).

Table 2. ***Estimated cost of farming organic matter***
On a brigalow soil used for grain cropping for 60 years.

Constituent	Depletion kg/ha/60yr	Depletion Kg/ha/year	Unit cost ($/kg)	Total cost ($/ha)	Annual cost ($/ha/year)
Carbon	40,000	666.7	0.02	800	13
Nitrogen	4,000	66.7	1.25	5,000	83
Phosphorus	200	3.33	2.60	520	9
Total				**$6,320**	**$105**

Source: Dalal, 2005, updated with recent prices for carbon and fertiliser.

The decline in organic matter has important impacts on soil structure and nutrient supply and also has a cost in terms of reduced productivity. Increased rainfall runoff and reduced crop production can set off a cycle of decline, which results in reduced biomass being returned to the soil and a faster rundown in soil organic matter.

The long-term nutrient management workshop focused on farming practices and systems which can reverse this general decline in soil carbon and soil fertility. A key aspect of most of the trials was to compare different rotations and farming systems, which not only involved different tillage and nutrient inputs, they sought to minimise disease and maximisecrop yield and water use efficiency.

Optimising inputs and maximizing the use of water for good crop production will improve soil health and crop production as well as being a win for the environment with reduced emissions of greenhouse gases.

4. Key principles of water efficient farming systems

A key principle on which to design a better dryland cropping system is the optimum conversion of moisture into grain. This is often measured as Water Use Efficiency (WUE). In turn there are key principles for water efficient farming systems, many of them tested in long-term trials

The widespread use of rotations involving canola and pulse crops, together with increased nitrogen fertiliser has increased WUE in recent years, but the potential for improvement across Australia is still high. Walcott et.al. (2006) has estimated that most southern cropping regions are only reaching 50-60% of potential efficiencies at the rate 20 kg grain per mm, suggested by French and Schultz (1984).

Starting off zero-tillage, there is a hurdle to climb and a delicate balance, which can turn against the system, says Albert Rovira,

Crop rotation is the key to disease and pest control in the early years.

Improved soil structure, disease suppression, and non-symbiotic N can enhance zero-tillage in the long-term.

Over the past fifteen years, long-term trials have provided data supporting the need to retain stubble, minimise tillage and introduce crop rotation in modern farming systems. These trials have generally run in parallel with adoption on farms, and while most were innovative in their day, the practice on farms has generally caught up with and overtaken them.

4.1 Zero-till and stubble produce long-term benefits

A zero-tillage system may start off with lower yields due to an increase in disease or pests such as snails or nematodes, but may improve with better soil structure, disease suppression and extra nitrogen input from freeliving soil organisms.

Rhizoctonia arose as a major problem with no-tillage in the first few years of the Avon trial. A planter with some soil disturbance helped, but the level of disease fell away with all treatments. Suppression of the disease built after a few years with the continued input of high C:N stubble.

In the initial years of zero-tillage, nitrogen supply to the crop may be reduced through less mineralisation and a build up of litter, while over the longer term increased nitrogen inputs are required for an increase in organic matter to occur.

Whilst there were no significant effects of tillage in several long-term trials (eg Mallawa trial site (1985-1993) and the Hart trial site over seven years), other factors are likely to have compounded with treatment effects, such as disease and the averaging of nitrogen effects. At the Avon trial site, WUE was maximised where root disease was low and nitrogen levels high. Yields from direct-drilled wheat (in a wheat/pea rotation) were impacted over the first five years by rhizoctonia, but gross margins were above cultivated treatments for the remainder of the trial. See figure 3. Cereal yields at Rutherglen (SR1) were maintained with stubble, but in the drought year of 1994 were 30% higher.

Any reduction in stubble from burning, cultivation or grazing can impact on soil carbon and the twin processes of disease suppression and non-symbiotic N fixation – which can contribute 10-20kg free nitrogen per hectare per year.

Beneficial effects of zero-tillage on soil structure were demonstrated in several situations, particularly hard-setting red brown earths. At Kupunda, the percentage of water stable aggregates was increased from 3-5% with tillage to 15-20% with direct drilling.

Organic matter was increased with direct drilling, but the effect disappeared with a change from the SIRODRILL which had minimum soil disturbance to the use of narrow sowing points which cused much more soil disturbance. This result confirms the fragile nature of the organic matter in red brown earths. Another significant effect of tillage at Kapunda was doubling in earthworm population and biomass.

The icing on the cake which results in an optimum system is an extra 10-20kg N/ha contributed by soil organisms, notably blue green algae in a process referred to as non-symbiotic nitrogen fixation (NSNF). A source of carbon is important for this process.

A nitrogen balance over 17 years at the Avon site showed 334 kg of extra nitrogen/ha which was unaccounted for. The 20 kg/ha/year difference is presumed contributed from NSNF.

An evaluation of potential NSNF for the Avon region by Gupta (See Roget and Gupta 2004) suggested an input of 10-15 kg/ha for the period January to June and further opportunity for some NSNF in spring. These figures assume the requirement for available carbon is met from retained stubble. NSNF is likely to be maximised by adequate carbon, moisture and high temperatures.

The potential for NSNF is highest in response to summer rainfalls. In March to May it is significant in southern Australia (5-10kg).

4.2 The need for rotation

Crop rotation and disease issues are often a starting point in the process of maximising WUE.

It is common for responses from nutrient application or zero-tillage to be negated by disease.

A consideration of diseases, pests and other systems effects (eg NSNF) is needed to explain some of the variable responses to tillage treatments and nutrients which occur in many of the long-term trials with different rotation programs. In some cases response to nutrient application or improved water use efficiency is affected by:

1. Seasonal yield factors – is there enough nutrient, or too much for the yield potential?
2. Dry soil conditions – nutrients may be unavailable in dry topsoil.
3. Root disease and nematodes may reduce nutrient uptake and yield.
4. Disease suppression has not developed.

Wheat yields were generally improved in rotation programs, with the most impressive result for Australia's longest running trial at Longerenong (LR1), which was established in 1916. The yield of continuous wheat in this trial for the period 1980-2004 ws 0.75t/ha, compared to 1.75t/ha for a wheat, barley, pea rotation and 2.3t/ha for rotations including grazing oats.

SCRIME is a more modern rotation experiment, set up in the same location as LR1 in 1998. The continuous wheat received N fertiliser (35kgN/ha/yr) and yielded 1.95t/ha (1998-2005) compared to 2.3t/ha in wheat/barley/pea or wheat/pea/canola rotations. See Table 4. An extra 300kg/ha yield does not sound much, but at these yield levels, it can double the profit from growing wheat.

In the Tarlee rotation trial yields of wheat after wheat and barley of 1.6 and 1.7 t/ha were improved to 2.33-2.47 t/ha after peas, lupins and beans over the years 1980-1985 (Schultz 1995).

4.3 Nutrient management

Nutrient management is important for long-term productivity and profit. The effects of regular applications of nutrients are discussed later in various chapters for nitrogen, phosphorus and other nutrients.

Crop removal is the major source of nutrient decline and over the long term, fertilisers need to be used in balance with nutrients removed.

Tillage, disease, pests, mycorrhizae and pH (liming) can all interact with nutrients and affect response to fertiliser.

In some cases there can be interactions between treatments and rotations. There are examples of zero-tillage being worse than stubble burnt treatments with no nitrogen added, but showing equal to or greater yields when adequate N is applied.

Further interactions have been demonstrated with liming in some instances. In the MASTER experiment at Wagga Wagga, liming was shown to increase arbuscular mycorrhizal fungi (AMF) which can improve crop access to P and other immobile elements, such as zinc and copper.

4.4 Storage of rainfall

Soil stored moisture is commonly understimated in winter rainfall areas and tillage and stubble treatments which reduce runoff, control summer weeds and reduce evaporation are likely to maximise soil moisture storage and crop yields in dry environments.

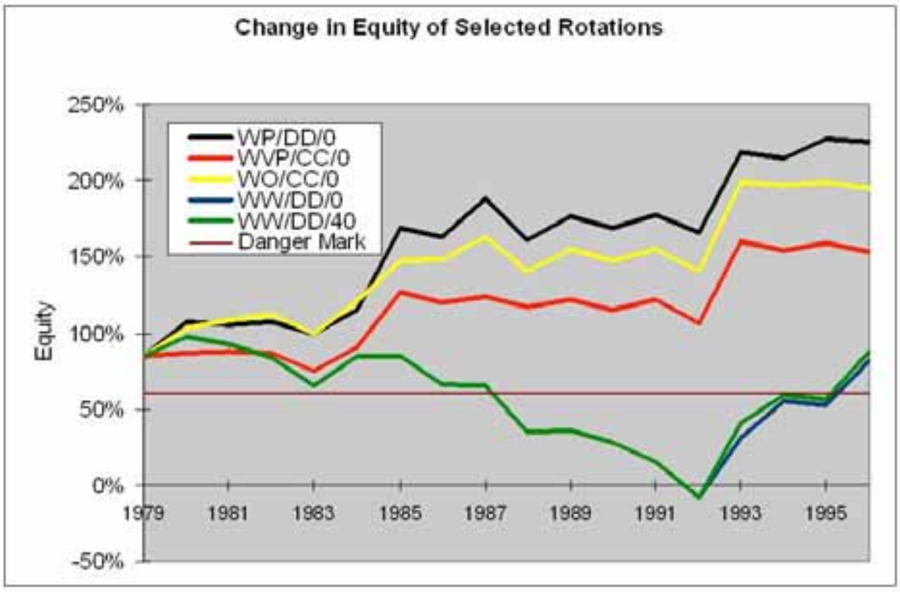
4.5 System profit requires evaluation

Crop rotation with pasture or pulse crops may produce the highest average wheat yields, but rotations need careful economic comparisons to decide which is the most profitable.

Trials showed that rotations which reduced root disease gave the highest yields, while pasture legumes or pulses will provide nitrogen at low cost and low energy inputs. However, the optimum mix of crops needs to be considered in response to grain yields and income from various alternatives.

Increasing the percentage of cereal crops in the rotation may also increase carbon input, which aids disease suppression and NSNF. In the SCRIME trial a wheat/barley/pea rotation had similar yields to a wheat/pea/canola rotation, and superior yields (from the wheat) to a wheat/lupin/pea rotation.

Figure 2. Change in Farm Equity of Selected Rotation and Tillage Treatments - Avon trial

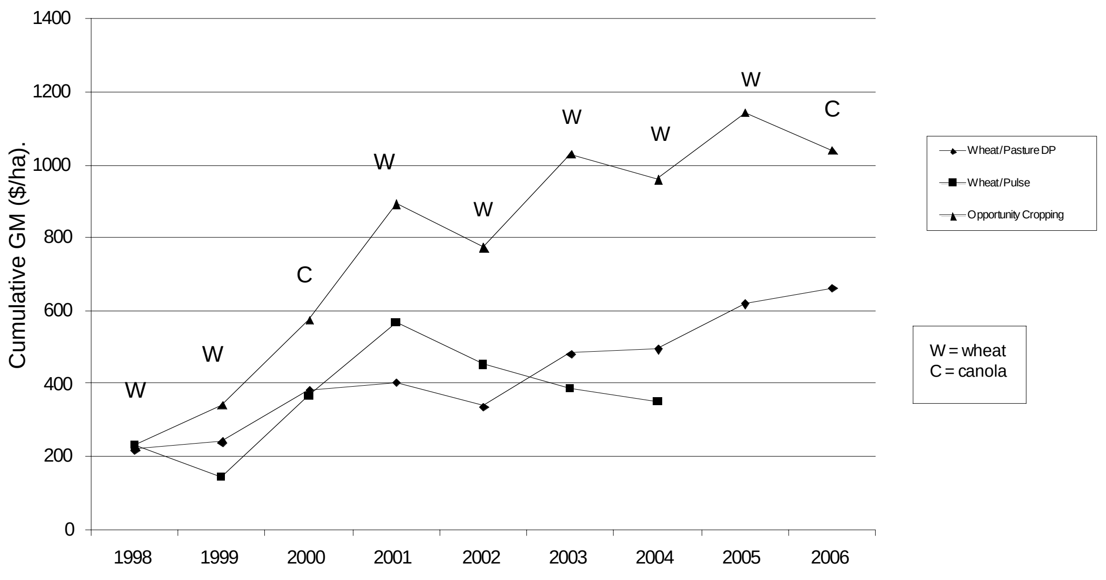


At Waikerie, the highest gross margin was produced by 'opportunity planting' of canola in years with good starting moisture and time of planting

An economic analysis of the rotation treatments at Avon was undertaken by Roget and Krause (reported by Rovira) and showed considerable difference in the outcomes over time.
Wheat and peas direct drilled was significantly more profitable than the next most profitable option of wheat and oats sown with conventional cultivation. Continuous wheat performed poorly in economic evaluation, but has shown some improvement in recent years with the advent of varieties with better disease resistance.

A trial at Waikerie (in a dry enviroment where crops like canola are considered risky) compared wheat/pulse and wheat/pasture rotations with an opportunity cropping system whereby canola was planted in years with a favourable start to the season. Despite the expected benefits from nitrogen contributed from the legumes, low grain yields from the grain legumes resulted in lower economic returns from the wheat-pulse system. See Figure 3.

Figure 3: Cumulative gross margins from cropping systems at Waikerie



Source: Rovira paper – Long term Nutrient Management Workshop

5. Long-term Nutrient Management - Nitrogen

There are several important considerations with respect to the long-term management of nitrogen:

1. Soil nitrogen content is closely related to soil organic matter (SOM) and mineralisation processes. As SOM declines, N is mineralised and is used by crops or leached. Conversely, if SOM is to increase, additional N is required above and beyond crop requirements.
2. Denitrification of N and the release of nitrous oxide (N2O) is not only a loss of N from the system, it is an important greenhouse gas.

3. Excess nitrogen in the soil profile can be leached below the crop rooting depth.
4. Total nitrogen supply and processes such as leaching have an affect on soil acidification.
5. Crop removal is the most important loss of N from cropping systems, with approximately 20 kg N removed per tonne of grain with 12% protein (eg wheat) and 16 kg N removed per tonne of grain with 9.6% protein (more typical of barley).

5.1 Nitrogen Fertiliser efficiency

Long-term application of nitrogen can be quite efficient, with minimal losses from denitrification and leaching in most farming environments.

A common assumption has been that around 50% of fertiliser applied is used by the crop in the season of application. But this does not mean that fertiliser is needed at twice the replacement level. Nitrogen is in a constant state of flux between soil biota, organic matter and mineralized reserves, with some of the fertiliser applied each year moving directly into soil biota and organic matter.

The long term efficiency of nitrogen fertiliser application can be high, provided leaching and denitrification are managed to minimize losses. In the Avon trial, the long-term nitrogen balance was positive with an extra 334 kg of nitrogen/ha measured over 17 years which was presumed to have come from non-symbiotic fixation by soil organisms (Table 3). This result would suggest, that at least in some instances, minimal losses of N occur from leaching or denitrification.

Table 3. N budget for 17 years of continuous wheat at Avon, South Australia, 1979-1996.

N source or sink	Calculation details	Net change in N (kg/ha)
Soil N	Total N (0-10cm) 1979 = 0.140% (+/- 0.005) 1996 = 0.135% (+/- 0.005) N from soil OM (Soil bulk density 1.2g/cc)	+ 60
Fertiliser N	No fertiliser added	0
Grain N	Total grain harvested = 19.7 t/ha Average grain N = 0.020%	- 394
Total N deficit		334
Annual N deficit		19.7

(Source: Gupta *et al.* 2006)

In most of the long-term trials, rotations with legumes, either pastures or pulses were used and the long-term nitrogen balance was positive due to the legume input. For example, the LR1 roation at Longerenong showed higher values of total soil N than other treatments involving wheat, oats and fallow (0.086% or 1000 kg N in the top 10cm vs typically 0.063% or 756 kg N – assuming a bulk density of 1.2)

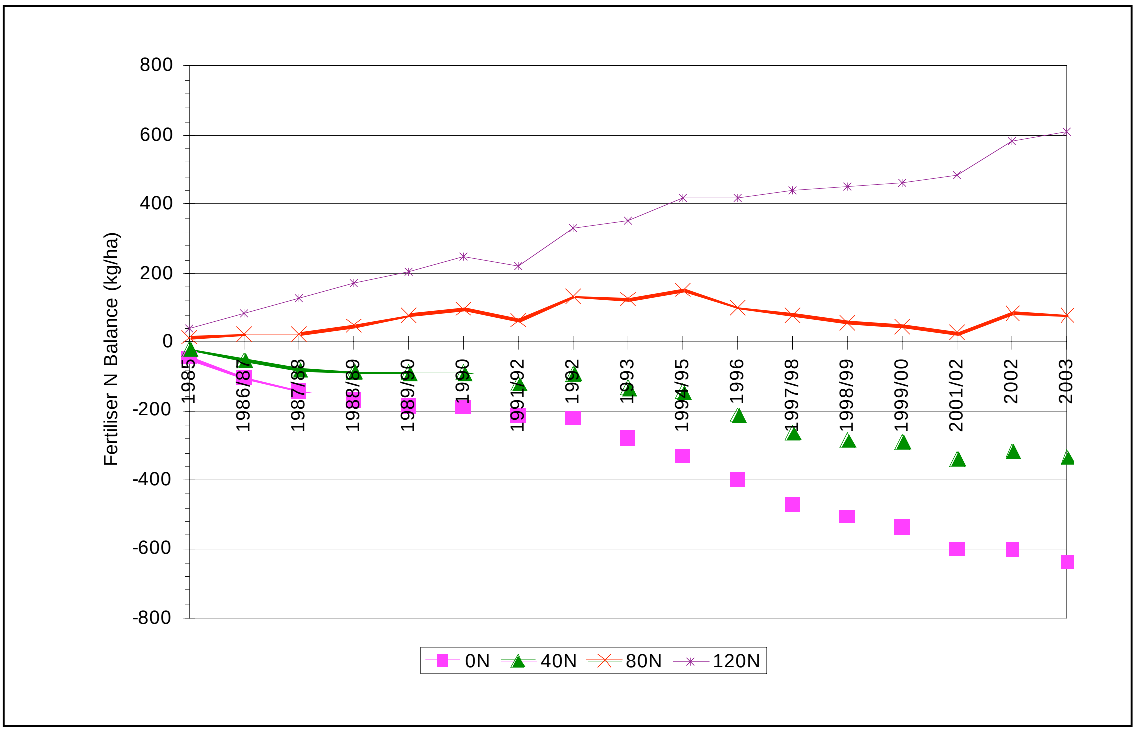
In the SCRIME trial (1998-2005) the Total soil N declined, despite the net N balance being positive for all treatments except continuous wheat. See Table 4.

Table 4: Net Balance for N and total soil N for SCRIME (1998-2005)							
	Wheat yield (t/ha)	N fertiliser input	N fix kg/ha/yr	Grain N removal	Net balance	Total soil N %	Change in N * 0-10cm
Continuous wheat WWW	1.95	35	0	41	-6	0.081	-120
Wheat/barley/peas WBP	2.27	17	45	56	+6	0.077	-168
Wheat/lupin/peas WLP	1.87	13	58	40	+31	0.083	-96
Wheat/peas/canola CT WPC	1.96	24	36	41	+19	0.083	-96
Wheat/peas/canola WOP	2.37	24	33	43	+14	0.081	-120
Wheat/chickpea/fallow WCpF	3.07	12	40	34	+18	0.074	-212
*Starting soil N: 0.091%, change is the reduction in total soil N in the top 10cm, with 1.2 bulk density							

The long term efficiency of nitrogen fertiliser on clay soils in northern grain belt has also found to be high with soil N levels remaining constant at Colonsay on the Darling Downs, when fertiliser N is applied at a rate of 80 kg N/ha is close to the removal of N from the soil over 18 years (Figure 4).

At lower rates of fertiliser application there was a rundown in the nitrogen reserves, while at higher rates (of 120 kg/ha N) there was a build up of N.

Figure 4: Nitrogen Balance over 18 years cropping at Colonsay Qld.



Source: Lester and Dowling 2005.

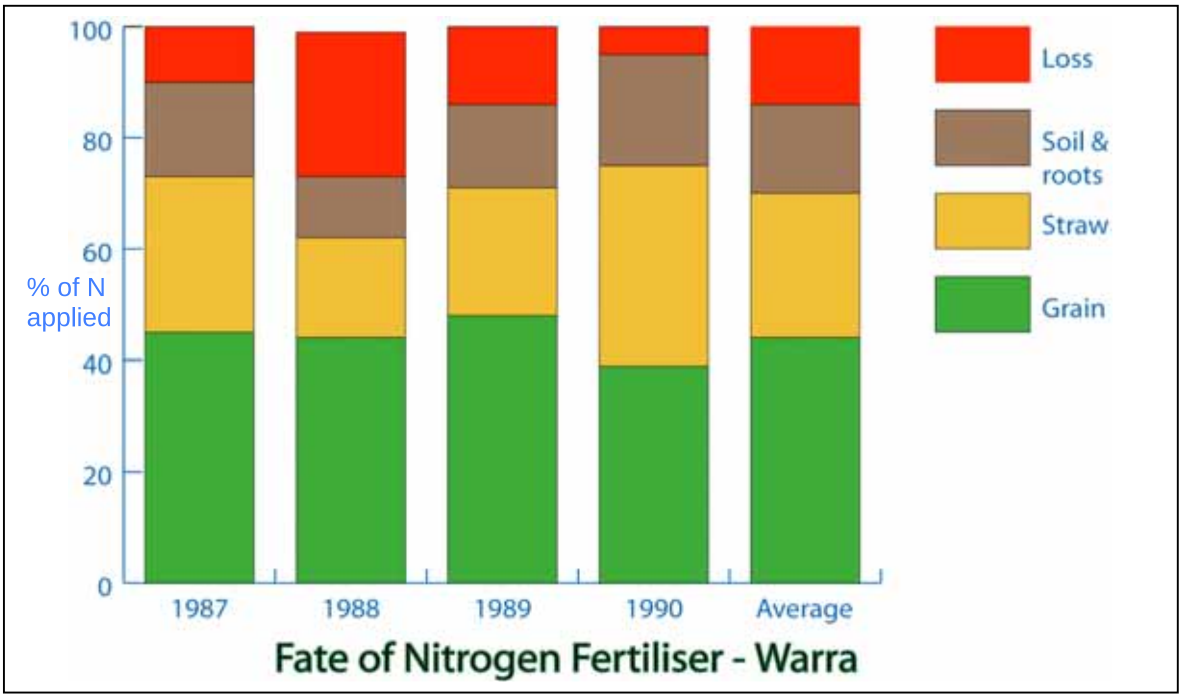
5.2 Denitrification losses

Denitrification is one of the main ways in which N can be lost from the soil system.

In a review of literature on the fate of fertiliser nitrogen applied to duplex soils in southern Australia, Fillery and McInnes (1992) report that between 10 and 40% of applied 15N can be lost, irrespective of time of application to wheat. Denitrification is believed to be the chief cause of loss of 15N.

Research by Strong on the fate of nitrogen fertiliser over 4 years at Warra in Queensland, measured by using isotypes of nitrogen. The loss (assumed to be the 15N enriched source of N not recovered) varied from 5% in a dry year to 26% in a wet year (1988) with an average of 14%. See Figure 5. Losses were mostly assumed to be through denitrification.

Figure 5: Fate of N fertiliser applied to wheat crops at Warra



As indicated by the positive nitrogen balance over time at Avon (Table 3) losses from denitrification may not be as high in all situations or at least with compensation from non-symbiotic nitrogen fixation the losses are not serious to crop production over the long term. However, high nitrogen efficiency depends upon minimising or managing denitrification.

The denitrification process requires anaerobic conditions and a readily decomposed source of carbon in the form of fresh straw or plant material. There is a time lag of approximately 24 hours for a build up in bacteria populations to produce significant output of nitrous oxide. These factors mitigate against denitrification losses and the rain which causes the waterlogging event can move much of the nitrate N, below 10cm where denitrification is minimal.

It has been assumed the loss of N by denitrification may be reduced in some instances by appling N late in the fallow, or at planting time, although this was not the conclusion of Fillery and McInnes (1992).

Waterlogging and denitrification is enhanced by compaction layers resulting from tillage. If zero-tillage, combined with controlled traffic creates better soil drainage, then it is likely to reduce temporary ponding on flat clay (or duplex) soils which enhances denitrification.

5.3 Leaching of Nitrogen

Leaching of nitrogen below the root depth is another pathway for loss and reduced efficiency of N fertiliser use. Leaching can occur quickly in sandy soils, but it may take several years for surplus N to reach the bottom of the soil profile on the clay soils in a dry environment. It may sit there for a few more years until a wet period pushes it further downwards. As shown in Table 5, large quantities of N can build up in the soil profile of clay soils.

Table 5. Soil nitrate prior to sowing in the Hermitage Fallow trial (Warwick, Queensland)

kg N/ha	MTSB	MTSR	NTSB	NTSR
1993 (0-1.5 metres)				
0	68	61	77	51
23	109	67	132	93
69	302	255	438	164
2003 (0-1.5 metres)				
0	102	82	136	52
30	226	126	167	95
90	785	600	826	367

MT – Mechanical Tillage, SB – Stubble Burnt, NT – No Tillage, SR – Stubble Retained

From Thomas 2005

In the Fallow Management trial at Hermitage (data shown in Table 5 from Thomas 2005), 800 kg of excess N was shown to buildup after long term use of 90 kg N/ha each year Around 25-30% of applied N was lost below 1.5 metres over 20 years. This trial has grown only winter crop and if grain sorghum had been included in the trial it is expected that N use would have been much higher.

5.4 Some short-term interactions with N supply

1. The rate of mineralisation of N during the season differs greatly in different paddocks and from different rotations.
2. Soil test levels after canola or pulse are similar, but mineralisation during the season is much greater with pulses.
3. Nitrogen at seeding and the mineralisation is affected by summer rainfall events and summer weed control.

Available phosphorus increases over time on some soils, while on others there is some immobilisation.

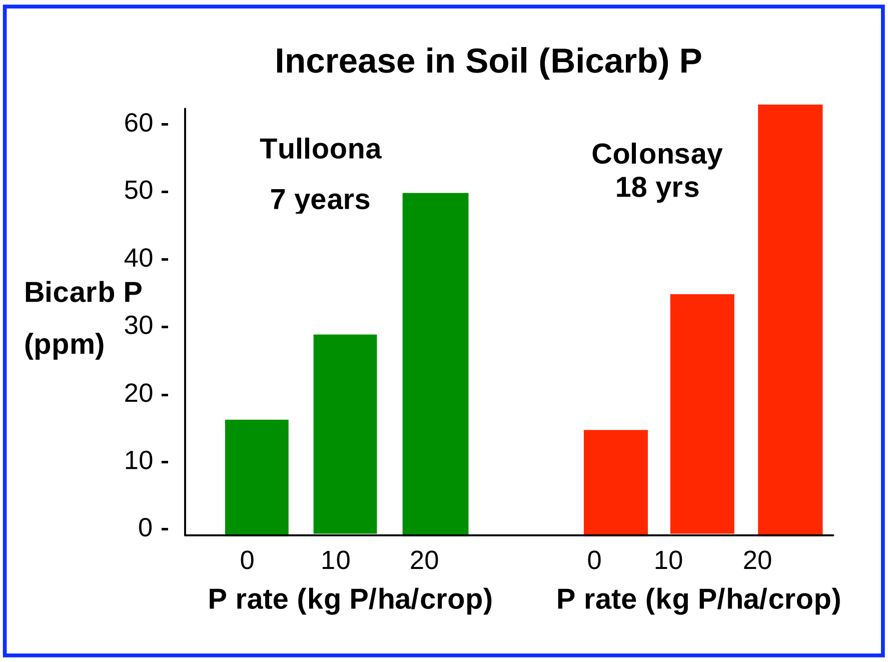
P may come from insoluble forms or be redistributed from lower levels to the topsoil.

Phosphorus fertilisation of soil has shown different effects on different soil types, depending upon the soil chemistry and the immobilisation of P.

In some cases there have been increases in Bicarbonate test level of soil P over time, despite P applications being less than crop removal. In other soils, P residual from fertiliser application declines over time and in extreme cases, such as the highly calcareous soils of the Eyre Peninsula, the availability of recently applied P can be very low.

A long term fertiliser trial on a black vertosol on the Darling Downs at Colonsay, has shown soil P to remain constant over 18 years, at 14 ppm P, where no fertiliser has been used, despite the export of 165 kg P in grain (Figure 6).

Figure 6: Increase in soil phosphate with P fertiliser Colonsay trial, Darling Downs



(Lester and Dowling 2005)

One effect here is the mobilisation of P from insoluble forms in the soil to maintain soil test levels. A second possible effect is that there is redistribution of P from lower levels to the surface. A reason to suggest it is not all due to redistribution, is that this is a cracking soil with significant downwards redistribution of surface soil whenever there is a cracking event followed by rain.

At a moderate level of P fertiliser (10 kg/ha/yr), the soil test increased from 14 to 28 ppm bicarb-P, despite the equation that crop removal was in excess, by 34 kg of the P applied (180kg).

A similar buildup of Colwell P has appeared on a vertosol at Longerenong in the LR1 Rotation, established in 1916. (See Table 6) There was no baseline soil measurement, but a fenceline comparison shows that colwell P levels have rise with fertiliser use, despite the net balance being close to zero and total P levels not significantly higher than the fenceline (as in FWOg and WOFOg).

Table 6: Net Balance for P LR1 (1980-2004) and P measured in 2005							
		Wheat yield (t/ha)	P Fert input kg/ha/ yr	Estimat eof P remova l	Net balance kg/ha/ yr	Total P mg/kg 2005	Colwell P 2005 mg/kg
Continuous wheat	WWW	0.75	10	2.7	+7.3	486	69
Fallow/wheat	FW	1.57	5	4.1	+0.9	367	52
Fallow/W/O grazed	FWOg	2.29	3.3	3.7	-0.3	307	40
Wheat/barley/peas	WBP	1.75	8.4	5.1	+3.2	341	40
Wheat/oats/peas	WOP	1.65	6.7	5.5	+1.2	329	47
Wheat/oats grazed/F	WOF	2.05	7.5	4.6	+3.0	330	66
W/oats/F/O grazed	WOFOg	2.34	3.8	3.9	-0.1	322	50
Fenceline						295	18

Reactions which reduce P residuals:

1. ***Precipitation or adsorption reactions***
2. ***Inaccessibility***
3. ***Leaching – in sands with high rainfall***
4. ***Crop uptake***
5. ***Grazing and redistribution***

Highly calcareous soils respond better to fluid P fertilisers. Precipitation rather than adsorption appears important. Colwell overestimates available P –up to 3 or 4 times the labile pool P

A different reaction occurred at Mallala, in South Australia. On a solonised brown soiil of moderate soil P status, Colwell P declined slowly in unfertilised soil, just declined with 10kgP/ha and increased with higher P rates. Where 10kg P maintained soil P, the apparent uptake was 5.6 kg/ha with an efficiency of 66%.

A study was undertaken to investigate the effects of tillage and crop rotations on the stratification of P and the distribution of P in different soil pools (labile – resin P, and less labile – bicarbonate and acid extractable) in three long-term trials in Victoria.

A greater proportion of P was tied up in the less labile pools in the Vertosol, compared to the lighter textured Calcarosol. P levels were higher in the direct drill treatments, suggesting a change in the dynamics of organic P in the soil, but tillage did not signifiantly affect the vertical distribution of inorganic P in the profile.

The general conclusions from long-term trials is that at P rates commonly used in commercial fertiliser applications, the cropping systems are mostly in a positive P balance and in many instances soil P levels are steadily rising. Most of this additional P is in pools that are sparingly soluble in the short term.

7. Long-term Nutrient Management – Other nutrients

7.1 Potassium

The current soil tests do not provide a good picture of the rundown in potassium reserves because they only measure the available or readily extractable K. This can change in response to soil moisture conditions and the soil K tests provide only a ‘snapshot’ in time, from which the availability of K to the plants is extrapolated.

The critical value identified in Queensland from a number of studies is around 0.2 meq/100g or 80 mg/kg K. Below this level, K deficiency is likely to occur, while above 0.4 meq/100g or 160 mg/kg, there is likely to be adequate K for the next crop.

K is becoming more of an issue on some of the lighter soils in southern Australia.

Canola windrow effects are sometimes misdiagnosed as N deficiency

Reliance on the 0-10 soil test may miss a problem which is most acute in 10-30cm layer.

According to Mike Bell, several factors affect the interpretation of soil tests and the decision to use K fertiliser. They include:

1. There is commonly release of K from insoluble forms.
2. K does not readily leach in clay soils.
3. K reserves are being depleted at depth and moved to surface.
4. Uptake of K is rapid during critical periods - usually 30-60 days after sowing.
5. The top soil needs to be wet during the critical period, and/or the subsoil supply of K may become important.
6. Grain legumes and cotton have a greater demand and are more responsive to K.
7. Large amounts of K are removed in hay and silage crops.

The large amount of K in the stubble of crops (eg. 15% of K uptake by wheat is removed in grain) means large quantities of K are returned to the soil surface. It also means large quantities of K are removed in hay or silage production and removal.

7.2 Sulfur

Sulfur is an emerging issue due to organic matter rundown, on soils where there is no gypsum in lower layers. Testing for sulfur has some problems due to seasonal factors – as to whether enough S is mineralised in a season.

7.3 Zinc

There are yield responses from zinc on some soils. Zinc can be applied as a small amount every year or a boost every few years.

Water soluble zinc may work better on alkaline soils. The residual effectiveness of zinc depends upon soil type – from 3 years to 13 years.

7.4 Copper

Some isolated areas have high yield response to copper, which was only detected by plant tissue testing. Long lasting effect of around 20 years from 7 kg/ha of copper sulphate.

8. Long-term management of pH and liming

The MASTER trial at Wagga Wagga showed lime + P to almost double crop yields, while stocking rate on pastures was increased by 25%.

After an initial application of 3.7 t/ha, the annual rate of lime needed to maintain pH levels is 1.5t/ha/6 years or 250 kg/ha/yr .

Soil acidification is an important problem in the 500+ mm rainfall zone in south-eastern Australia. Farming practices, particularly those which add nitrogen (from fertiliser or legumes) can accelerate the acidification process.

The MASTER trial, established on a farm ot the south of Wagga Wagga has demonstrated that lime can be used profitably for crop and sheep production and that sub-surface acidity can be slowly ameliorated.

The target pH was 5.5 over 6 years. An application of 3.7 t/ha lifted the pH from 4 to around 5.5, which then declined to 5 over the next 6 years. Extra lime at the start will not only improve pH, it will provide some excess to leach into the subsoil and improve pH there. The rate now estimated to main the target level is 1.5 t/ha/6 years or 250 kg/ha/year.

Leaching is higher with lime and may be expected to increase N loss, but if production is higher with liming and crop rotation, then crops will use more N and reduce leaching.

Liming makes P application more efficient, partly due to an improvement in the mycorrhizal population, which also helps plants to access other immobile nutrients Zn and Cu. Liming also increases Mg concentration over time which helps to reduce N leaching. It also reduces grass tetany in pastures.

At the Tarlee long-term rotation trial site, the effects of combined inputs (wheat-lupin N, stubble retention and N fertiliser) reduced the pH (0-10cm) from a starting value of 6.1 to 4.5 after a 14 year period. The effects were less with lower N input and stubble removal or burning, however these corresponded with lower yields and less grain removal. The highest WUE was 10 kg/ha from wheat in a wheat-beans rotation with 80 kg N.

While there was additional yield from the use of N fertiliser in all rotations, it is likely that 80 kg N was in excess of crop requirements, as shown by similar yields of wheat after peas, lupins and beans with 40 and 80 kg of applied N. Excessive N and leaching of nitrate is likely to accelerate the decline in pH.

In the long-term experiment at Rutherglen (SR1) a gradual decrease in pH has occurred over 25 years, from initial pH levels greater than 5, to an average of 4.94 in 1988 and 4.6 in 2006. There have been no significant differences between stubble and tillage treatments.

9. Long-term Management of Organic carbon

Farming practices which build rather than deplete soil carbon will not only reduce greenhouse emissions, they will improve soil health and productivity. Practices which enhance organic matter will maintain or improve soil structure, provide good conditions for soil biota, improve the soil water balance and the productivity of soils over time.

There has been a general rundown in soil carbon and nutrients in most cropping areas, but particularly in northern cropping areas (shown in Figure 1 on page 4).

The long-term trial LR1 and Longerenong showed a similar decline of around 50% of soil carbon on the trial site, cropped since 1916, compared to the fenceline. The highest carbon and nitrogen levels were measured in rotations of wheat which included peas, with the lowest in continuous wheat and where fallow was used.

Table 8: Carbon Balance, Longerenong Rotation trial with N anc C measured in 2005

		Wheat yield (t/ha)	Total soil N %	Estimat eof N * kg/ha	Total soil C %	Estimat e of C* t/ha	Loss of carbon ** t/ha
Continuous wheat	WWW	0.75	0.070	840	0.93	11.6	13.8
Fallow/wheat	FW	1.57	0.056	672	0.91	10.9	14.5
Fallow/W/O grazed	FWOg	2.29	0.063	756	0.93	11.6	13.8
Wheat/barley/peas	WBP	1.75	0.085	1020	1.10	13.2	12.2
Wheat/oats/peas	WOP	1.65	0.087	1044	1.11	13.3	12.1
Wheat/oats grazed/F	WOF	2.05	0.061	732	0.85	10.2	15.2
W/oats/F/O grazed	WOFOg	2.34	0.066	792	0.92	11.0	14.4
Fenceline			0.162	1944	2.12	25.4	

* In top 10cm, assuming a bulk density of 1.2 ** compared to the fenceline data

LR1 is the Longerenong rotation trial established in 1916

A long-term trial at Wagga Wagga (the SATWAGL trial) demonstrated that good rotations and no tillage can maintain soil carbon, while a decline of carbon is greatest where stubble is burnt and tillage is used. A summary of these effects is presented in Table 9.

Table 9: Soil Carbon storage, and change in soil carbon: 1979-2000 (0-10cm)					
	Stubble	Tillage	Soil carbon (t/ha)	C balance	Change in C kg/ha/yr
1. Lupin/wheat	Retained	No-till	22.3	-1.29	-10
3. Lupin/wheat	Retained	3 cultiv	20.3**	-3.59	-215***
4. Lupin/wheat	Burnt	No-till	21.4**	-2.19	-150**
6. Lupin/wheat	Burnt	3 cultiv	18.1***	-5.75	-306***
9. Wheat/wheat	Burnt	3 cultiv	16.8***	-7.03	-419***
10. Wheat/wheat + 100 N	Burnt	3 cultiv	17.8***	-8.51	-335***
11. Subclover grazed/wheat	Retained	3 cultiv	22.8	-0.80	-79
12. Subclover mulched/wht	Retained	No-till	27.9	4.43	200***
13. Subclover mulched/wht	Retained	3 cultiv	23.9	0.39	-6
SATWAGL long-term trial Wagga Wagga					
*,**,** significant at P<0.5, >0.01 and >0.001					

The Cooperative Research Centre for Greenhouse Accounting has recently completed a study to quantify the effects of farming on soil carbon. The experimental site, at Hermitage was established in 1968 and wheat has been grown for 35 years.

The study established that no-till farming does not have the same carbon impact in Australian as it does in the US. The CRC study found no significant difference in carbon between no-till and tillage except when nitrogen fertiliser was added.

www.greenhouse.crc.org.au/research/a1.cfm

Can farmers improve soil carbon?

The SATWAGL trial shows a small improvement of soil carbon is possible with good cropping systems.

Dalal (2005) noted a small increase in organic carbon, of approximately 1.5 t C/ha over 33 years, from depleted levels, when no-tillage was used at the Hermitage Research Station fallow trial, in Queensland. Carbon only increased where fertiliser was applied. This figure appears to have been used by the Australian Greenhouse Office, as part of their supporting data to say that the potential for accumulation of carbon in agricultural soils is low.

Whilst the general conclusion of Dalal is that insufficient biomass is produced by grain crops in semi-arid cropping environments to maintain high carbon levels, the results of the Hermitage trial underestimate biomass input because the trial was restricted to winter crop which was badly affected by root diseases. Grain sorghum has approximately twice the grain yield and biomass potential of wheat at Hermitage and had it been used in a crop rotation system, the potential for organic matter buildup would have been much greater.

Grass legume pastures have been demonstrated to have a more positive effect on soil organic C (550-650 kg C/ha/year in two rotation trials in a Vertosol at Warra, Queensland), but two year rotations of lucerne-wheat and medic-wheat after 8 years under conventional tillage had a negligible effect on organic C concentrations (Dalal *et. al.* 1995), thus confirming the findings of Holford (1990).

The emphasis on pasture rotations in southern Australia has been on grass-free or pastures with a high legume component and there have been similar conclusions that organic matter can be maintained, but not greatly advanced with the return of low C:N legume biomass to the soil.

Practices which build soil carbon

1. High yield - high biomass crops

Good crops build higher levels of soil carbon, says Jeff Baldock of CSIRO.

Sequestering carbon is not free, it requires N and P.

This is not necessarily a financial negative for farmers if the improved organic carbon system can release more N in a high yielding season.

Wheat is the main dryland crop in Australia, with generally higher carbon return to the soil than pulse crops. In the northern cropping areas, grain sorghum will produce around 1.5 times the biomass of wheat and twice the biomass of dryland cotton and chickpea.

2. Eliminate tillage

In ten long-term studies of no-tillage in the USA an increase of 1.08t/ha/yr of SOM (0.6 t/ha C) was measured, compared to a decline of 0.3t SOM/ha/yr where ploughing was used (Reicosky 2001).

The effects of zero-tillage are less in Australia, because the potential to store carbon is lower than in the USA. Rainfall is generally lower (with lower biomass input) and there is a longer period of warmer weather during the year for mineralisation of SOM.

Freebairn (1998) reviewed tillage trial data for clay soils in northern Australia and found that zero-tillage was able to halt the decline in SOM, while one or more cultivations a year (minimum or reduced tillage) is likely to result in a continuing decline in SOM. Freebairn acknowledged that most of the tillage trials involved wheat. Some farmers in high yielding sorghum growing areas have measured increases in SOM with zero-tillage.

Zero-tillage helps to maintain or improve organic matter, particularly in northern cropping areas where the potential for mineralisation is high.

Zero-tillage also saves energy on farms, which combined with carbon storage can minimise greenhouse gas emissions.

Chan (2003) reviewed field trials on conservation tillage on light textured soils in southern Australia and found zero-tillage could increase soil organic carbon levels only in the higher rainfall areas (>500mm). In the drier areas, soil organic carbon continued to decline, even under conservation tillage.

However some increases in SOM with zero-tillage have been reported by farmers in lower rainfall areas. One example is from Hyden in Western Australia, where monitoring of a number of paddocks over the period: 1994 to 2001, showed an average increase from 0.7% Organic Carbon to 1.2% OC when zero-tillage was used (Crabtree 2002).

While zero-tillage is usually essential to building SOM, it also has other effects on minimising greenhouse gases. Fuel use is reduce from 76 to 46 litres per hectare in cropping systems in southern Queensland (Tullberg and Wylie 1994) and in conjunction with controlled traffic, zero tillage will minimise compaction and reduce emissions of the greenhouse gas nitrous oxide. This loss of nitrous oxide mostly occurs on flat land. Zero-tillage reduces surface ponding after rainfall, which results from a plough pan or compaction layer below the cultivated depth.

3. Maintain soil fertility

A decline in soil fertility will reduce crop biomass and carbon input. Less ground cover is produced by nutrient limited crops, which in turn may result in less moisture stored and lower yields from subsequent crops. There has been a general increase in nitrogen fertiliser use in Australia, but applications are still less than crop removal.

One of the problems of soils with low organic matter is that there is not enough organic N reserves to mineralise extra N to help produce big yields in years with good rainfall.

Feedlot manure contains around 20 kg N and 7 kg P per tonne worth $40 if applied as urea and MAP.

If it can be bought and applied for $20/t it can supply nutrients at half-price.

Poultry manure is more valuable with 22kg N and 13 kg P/t.

K, S and Zn are an important bonus of using manures.

4. Feedlot, pig and poultry manure

Animal manures can not only add nutrients more cheaply than mineral fertilisers, they also add useful amounts of organic matter.

Around 1.2 million tonnes of feedlot manure is produced in Australia each year, along with half a million tonnes of pig and poultry manure. The proportion of grain production used for animal feed continues to increase and have reached the point where exports of grain from eastern Australia are now less than half of total production. Use of animal manure will reduce the need for and the energy cost of artificial fertilisers, add to soil carbon and boost soil fertility and soil health.

Farmers are often concerned that manure is difficult to manage compared to fertiliser. The use of manure can be simplified by applying it as a phosphate (P) fertiliser. If the optimum application of P is considered to be 8 kg P/ha/yr then an application of 10 tonnes of aged manure will apply 70 kg P/ha and last up to 8 years. Used in this way there is adequate potassium (K), but nitrogen needs to be boosted with other fertilizers, depending upon the mix of grain and legume crops and their yield and nitrogen demands.

5. Pasture leys will build SOM.

A grass-legume pasture can build soil carbon levels by more than 1 t/ha/yr in some situations which could lift the organic carbon level in a typical soil by 0.05% p.a. Perennial grasses grow a big root system which contributes to below ground SOM return as well as surface litter.

In drier cropping areas it is common to use pasture leys of 3 to 4 years to restore fertility (boost nitrogen from legume input) and organic matter on rundown cropping soils. Excessive tillage should be avoided at the end of pasture phase, or much of the added SOM will be rapidly depleted.

What is a good level of Soil Carbon?

Firstly we should be clear about the difference between soil carbon and SOM. SOM is the organic fraction of the soil, exclusive of undecayed plant and animal residues. This is often referred to as humus, except that humus does not include soil microbial biomass.

In practice, SOM is measured as soil organic carbon (SOC) and includes all plant and animal residues, living or dead microorganisms, charcoal *and* humus. To convert SOC to SOM we multiply by 1.724.

The optimum level of soil carbon will depend upon the age of the cultivation and the rainfall, which affects biomass input. Most organic matter (apart from charcoal) is in a constant state of turnover, where it is decomposed and replaced by fresh litter or soil fauna over a short time period of 3 to 5 years.

Various fractions of soil carbon have different effects:

1. *Crop residue*
2. *Buried crop residue*
3. *Particulate organic matter (POC)*
4. *Humus (less than 53 microns)*
5. *Resistant organic matter – dominated by charcoal – often ones coming out of grassland, where there have been regular fires*

Pastures have a big proportion of the carbon as POC, whereas humus tends to dominate in cropping systems.

The level of organic matter in the soil is in a fluid relationship between the amount of carbon being added and the rate of decline. In sub-tropical areas of Australia, the rainfall can produce a reasonable biomass input, but the high temperatures and mineralisation which can occur over the whole year results in a rapid rate of decline.

Organic carbon levels in soils in higher rainfall areas (600-700mm in Northern Australia and 400-500mm in southern Australia), commonly start around 2% and decline to around 1% after 50-80 years of cultivation. It is difficult to build OC back up, but with good management and high yielding crops, a SOC level of 1.2-1.5% may be possible.

In lower rainfall areas the initial levels of SOC are usually lower and it is more difficult to maintain organic matter because crop yields and biomass input are lower and SOC levels of 1-1.2% appear more sustainable.

Interaction between soil carbon and soil structure

Farmers who make the change to zero-tillage often remark the crops are better from the first year, but the soil gets better over the next five.

The main benefits of zero-tillage are the moisture savings which can result from preserving soil cracks and/or maximum stubble cover. The secondary benefits are an improvement in soil conditions over time, which may provide an extra yield bonus.

At Biloela, a tillage trial was conducted for 20 years, during which time zero-tillage out-yielded crops grown with tillage by 24 to 30% (Freebairn 2007). For the past four years, zero-tillage has been imposed over all the previous treatments and on the land previously zero-tilled. Over these four years, crops on zero-tilled ground have outyielded the zero-tillage on cultivated ground by 64% (3.2 t/ha vs 1.97 t/ha).

The most recent crop of sorghum grown on land zero-tilled for 24 years, yielded 31% more (4.7 t/ha vs 3.6 t/ha) than sorghum grown as the fourth zero-till crop after 20 years of tillage. Moisure storage was up 30% at planting time (221 mm compared to 169 mm) and water use efficiency was higher as well.

The zero-tilled ground showed better porosity and higher organic matter. Organic carbon in the top 10 cm after 20 years of cultivation was 1.27%, compared with 1.61 for zero-tillage. There were three times as many earthworms in zero-tilled areas, than where cultivation was used. The poorer structure and increased compaction was letting less water into the soil and restricting root growth.

Different soils - different responses

Self-mulching soils are likely to respond differently to those which do not crack or have surface sealing. Zero-tillage does not show as much benefit from improved structure on self mulching soils, but by keeping the cracks open, can store more soil moisture at times.

Cracking soils are not likely to show nutrient stratification after years of zero-tillage because stubble and top soil gets washed down the cracks.

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Appendix 1: Papers presented at the Long-Term Nutrient Management Workshop – Adelaide – 4-5th June 2007

1. **Soil carbon dynamics under SATWAGL long term trial – implications for soil health and carbon sequestration under Australian farming systems**

   K Yin Chan and Damian P Heenan

2. **Long term liming experiment in southern New South Wales**

   Guangdi Li, Keith Helyar, Mark Conyers and Brian Cullis

3. **The effects of fertiliser rates on available soil nitrogen: The Hart trial**

   Peter Hooper

4. **P cycling in a wheat-medic rotation under different tillage and N fertiliser regimes.**

   Denis Elliott, and Angus Alston.

5. **Long Term Field Trials at Avon, Kapunda and Waikerie in South Australia to Study the Effects of Rotation and Tillage on Soil and Root Health and Profitability.**

   Albert Rovira, Gupta, V.V.S.R. and David Roget

6. **Long term experiments – nutrient balances and lessons in the Wimmera & Mallee**

   Rob Norton, Roger Armstrong, Roy Latta, Lauren Dart, Vu Dang, Caixian Tang, Charlie Walker and Rob Christie

7. **Phosphorus trials in the Victorian Wimmera-Mallee: grain yield responses**

   David Moody, Harm van Rees, Fiona Best and Cherie Reilly

8. **Long-term changes in soil nutrient status and crop yielss: 25 years of continuous stubble retention with crop/pasture rotations and 87 years of pasture response in north east Victoria.**

   Phillip Newton

9. **Crop Production in a rotation trial at Tarlee – J.E. Schultz, 1995**

10. **Soil Acidification as influenced by crop rotations, stubble management and application of nitrogenous fertiliser, Tarlee – Xu, et al. 2002**

11. **Highlights: Long-term Fertiliser Use Workshop: held in Toowoomba, March 2005** Peter Wylie

Appendix 2: Brief outline of the Long-term Trials in Southern Australia reviewed in the Long-term Nutrient Management Workshop

1. Sustainable agriculture through wheat and good legumes (SATWAGL).

This trial was set up in 1979 at Wagga Wagga (rainfall 550 mm) with the objective of managing soil nitrogen with grain legumes. The soil is a red earth (kandosol) with good structure.

The trial includes wheat-lupin rotations, with tillage and stubble management treatments. After 1988, the objective was changed to the identification of rotation, tillage and stubble management practices which can provide sustainable soil health and crop production.

After 21 years, all treatments lost carbon, except the no-tillage wheat with pasture rotation which had a level of 28 t/ha of carbon in the top 10 cm, compared to lowest treatment of 16 t/ha from continuous wheat, with stubble burnt, and a starting level 23 t/ha. No-tillage was more important than stubble burning with respect to carbon loss.

No-till wheat/legume programs had a long-term carbon balance of -1.3 tonnes of carbon after 21 years, compared to -3.6 t/ha for cultivated wheat/legume rotations.

A good correlation occurred between soil carbon the accumulation of organic P and nitrogen. After 19 years, mineralisable N of Wheat/Lupins under NT/stubble retained was 59% higher than that of Cultivation/stubble burnt.

Wheat with no N averaged 2.2t/ha, while continuous wheat with N yielded 3.2t/ha, compared with 3.6-3.8 t/ha for wheat/lupins. Wheat after clover pastures yielded around 2.8 to 3 t/ha.

2. MASTER Experiment. – Wagga Wagga

This experiment commenced in 1992 on a farm at Book Book, 40 km south-east of Wagga Wagga. Average rainfall is 614 mm. Treatments include tillage, pastures, liming and the management of acidification.

Rotations comprised three years of pasture and three years of crop, assuming the crop will use the nitrogen produced by pasture legumes. The soil pH is low (4.0) and acid tolerant varieties of wheat are needed. Lime is added every six years.

The target pH was 5.5 over 6 years. Rates around 3.7 t/ha lifted the pH from 4 to around 5.5, which then declined to 5 over the next 6 years, when a topup is made. Commercial rates of application 2.5/ha will lift pH to around 5.0. The extra 1.5 t/ha will not only improve pH, it will provide some excess to leach into the subsoil and improve pH there. The rate now estimated to main the target level is 1.5 t/ha/6 years or 250 kg/ha/year.

Leaching is higher with lime and may be expected to increase N loss, but if production is higher with liming and crop rotation, then crops will use more N and reduce leaching.

Liming makes P application more efficient, partly due to an improvement in the mycorrhizal population, which also helps plants to access other immobile nutrients Zn and Cu. Liming also increases Mg concentration over time which helps to reduce N leaching. It also reduces grass tetany in pastures.

Crop yields were almost doubled with lime and P. Lime increased stocking rate on pastures by 25%.

More details at the website; www.dpi.nsw.gov.au/primefacts Primefacts 31 to 38

3. **The HART site, South Australia**

Hart is in the mid-north of SA, with 450mm rainfall on a clay-loam. No tillage started taking on in 2000 when the trial started.

Over 7 years there are no trends in crop yields with different seeding systems. There has been no significant difference in grain yields or quality. No-tillage initially was lower yielding at lower N levels, but similar at the higher rates.

In the first three years of the experiment, the higher N treatments were yielding better across treatments. But in recent (dry) years, the higher N treatments have been worse due to haying off. The OC is 1.77 with no difference between treatments after 7 years. Nitrate N has changed, with 50kg N/ha more in the high nutrition treatments.

4. **Long-term P trial at Mallala, South Australia**

P cycling was measured in a wheat medic rotation under different tillage and N fertiliser regimes.The trial at Mallala around 50 km north of Adelaide was on a Solonised brown soil with a pH 8.3. The trial ran from 1985 to 1992. Treatments included 0-40 N, and 0,10,20 and 50kgP per rotation, in a two-year rotation of medic and crop with cultivation and no-tillage treatments. The 1985 P level was 15.5, but varied from 12 to 20.

Only a minor response of medic to P fertiliser was recorded, mostly in autumn rather than spring. A big response to P in grain yield occurred in 1995 and 1992, but responses to grain yield occurred only 4 out of 8 years and not in the dry years when rainfall was 50mm below average.

A slow decline in colwell P was measured on unfertilised soil – 0.9 units per year for first 4 years. Marginal decline occurred with 10 kg P (estimated requirement 6 kg P/ha/year) while soil P increased where 20 and 50 kg P were applied, with a lot of it in organic forms. Yields of wheat in 4 years were better with min-tillage was on top, while in 4 years cultivation was better. Ongoing concerns with CCN continued until the advent of resistant varieties. However the first resistant variety was not a good performer agronomically.
N response occurred only one year in 8, partly due to the good, grass free pastures. The medics were producing enough N.

5. **Avon Trial**

The trial started in 1978, at Avon, 100 km north of Adelaide, with annual rainfall of 280mm typical of the Mallee. It was set up to examine rotation and tillage effects on the fungus disease Take-all and on soil healthy and profitability.

Rhizoctonia arose as a major problem with no-tillage. A planter with some soil disturbance helped, but the level of disease fell away with all treatments. Biological suppression of the disease started to occur around five years after the start of the trial. An unexpected finding was there was significant non-symbiotic fixation of N (NSNF) associated with stubble retention. An overall deficit of 20 kg N/ha/year is presumed contributed from NSNF.

Factors supporting NSNF include adequate carbon for the fixation, moisture which is usually good in winter but temperatures are not favourable. The potential for NSNF is highest during January-February and 20-30 kg could be fixed if there are useful summer rainfalls. In March to May it is significant in southern Australia (5-10kg).
Profitability was greatest with a wheat/pea/direct drill/0N rotation, whereas WW/DD/40N had the lowest profit.

6. **Kapunda trial**

In 1983 a similar trial to Avon was started at Kapunda in the mid-north on a typical red-brown earth and 500 mm of rainfall. Three rotations were used: continuouse wheat (ww), lupins-w and pasture-wheat

With no-tillage, soil structure improved within 4 years with better aggregation and more earthworms. Organic matter increased with the Sirodrill, but this effect disappeared with a drill which had tines and more disturbance.

6. Waikerie trial

A third long-term field trial was established in 1998 at Waikerie in the drier part of the South Australian Mallee. Waikerie had minimal input, depending upon pasture to provide most of the N. The Avon trial showed higher inputs were more profitable. At Waikerie, it was considered risky to move to high inputs of P and some N and to grow break crops like pulse or canola.

One treatment involved growing canola in years with early rains and promise of 'above-average' yield potential. This resulted in the most profit.

Now the risk is actually lowered by the higher inputs – especially after organic matter has started to improve. The real issue is the frequency of the break crop and how risky it is. Normal productivity was achieving around 50% of the water limited potential. Heavy grazing, following and endemic wind erosion have resulted in low OC return to soils with limits on microbial activity.

Principles derived from Avon, Kapunda and Waikerie

1. Rotations are essential
2. Organic matter retention is essential
   - 2.1. Development of disease suppression
   - 2.2. NSNF
   - 2.3. Supply of plant available N
   - 2.4. Improved soil structure
   - 2.5. Increase in earthworms
3. No-till farming succeeds when rotations control disease
4. Profitability then increases with fertiliser (and control of root disease)
5. Flexibility is possible - putting high risk crops like canola in as a break crop

6. Wimmera trials: LR1, SCRIME (vertosol), MC14 (calcarosol)

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The National Land and Water Inventory suggests that the nutrient balance has an annual loss of 50 N and 10 P/ha per year. According to Robert Norton this is not correct.

The Longerenong Rotation, LR1 is Australia's longest running annual cropping experiment, established in 1916. Annual rainfall is 420 mm. The experiment compares 7 rotations: WWW, WF, FWoats grazed, WBP (wheat,barley,peas), WOP, WOgF, WOFOg. Wheat yields for WWW averaged 0.75 t/ha, compared to 1.75 for WBP and 2 t/ha for WOF. The average N balance for the period 1980 to 2005 indicated a decline in soil N of 12 kg N/ha/yr where no pulse was included and a slightly positive N balance where peas were grown.

The total soil nitrogen (TSN) on the fenceline is 0.16%. This has declined to around 0.085% in cropping systems with legumes, and 0.05-0.065% for non-legume systems. Soil organic carbon levels (SOC) on the fenceline are 2.12% compared to 0.9 – 1.1%, higher with N input from peas by around 0.1%. The decline has been around 140 kg C/year.

The SCRIME rotation established on land next to LR1 in 1998, includes modern crops and rotations. From 1998 to now includes some dry seasons, so has been a difficult time for long-term trials. There has been very little change in TSN, and SOC except where there is a cultivated fallow.

MC14 is a rotation trial on a (sandy) calcarosol in the Victorian Mallee region with rainfall of 335mm.

All rotations have shown to be in negative N balance, while the P balance has been positive with an annual application of 6 kg P. Concentrations of soil total P are rising, but most of this P is in pools that are sparingly soluble to crops in the short-term. Most of the extra P with zero-till is in the top 5 cm

An Incitec Pivot trial was established at Dahlen in 1996., on a vertosol, just to the west of Horsham. At this site Colwell P values are rising with P rate, which has also increased OC from 0.93 to 1.01. N did not increase SOC, but decreased soil pH from 7.3 to 6.9 Both N and P increased soil S levels.

When in lentils, P increased biomass and seed yield. The % N derived from the atmosphere did not change much, but N fix increased with the yield of the legumes in response to P.

Overall Conclusions from the Wimmera and Mallee trials are that apparent nutrient balances are positive for systems which receive moderate fertiliser inputs.

7. Mallee Trials – Birchip Cropping Group

Yield response from 46 trials 1982 to 1992, response is high with Colwell P levels below 15 ppm, dropping off with P levels over 20.

In one trial series, a time of sowing by P response trial, there was a greater P response with later sowing, possibly because early sowing has better root growth and higher capacity to explore the soil for P. In a second series, there was a large negative effect of sowing time on grain yields (eg Birchip grain yields were 2.6, 2.0 and 1.5 t/ha for May, June and July sowing) but there was no yield response to the application of P at either site for any time of sowing.

In a species response trial, wheat, barley, canola and pulse (field peas, lentils, chickpea and fababeans), were grown over three years at four sites. In 1999, the only response was at the low P (Colwell 14 P) at Donald, where wheat did not respond, but barley and faba bean responded. In 2000 and 2001 wheat responded along with fababean. Not surprisingly there was no response at the sites with 23 and up to 31 P. Faba bean responded at much higher rates of P, mostly up to 18 kg.

In a long term P application trial (with initial Colwell P of 22) a rotation involved growing wheat (2002), Barley (2004) and Oats in 2005. There was no response in wheat. Barley in year 2, showed some response from 5kg P. Average gross margins were similar. No P showed a decline in soil P, while at 10kg P soil levels were maintained and at higher levels the soil P level increased to around 40.

Birchip results confirm that it is rare to have economic responses with Colwell P above 20. An application of 6kg P/ha appears to provide most of the benefit, but this might not be enough if P is being applied to a crop for a future pasture as well.

In some soils the initial P application needs to be much higher than the crop P requirement. After a significant P application you may get to a stage when you put 6 kg P in and get 6 kg P out.

7. Rutherglen Long-term Trials

Stubble retention 1 and Stubble retention 2 (SR1 and SR2) are two trials established to test the long-term agronomic and eco-sustainability of stubble management and tillage under crop rotations.

One of the agronomic implications has been that herbicide resistance has caused problems with the long-term trials at Rutherglen.

Organic carbon will rise with a pasture in a rotation, but mostly the wheat lupin rotation will only hold C around the 1% level, while burning will decrease soil C.

8. Tarlee Trial

This trial at Tarlee in South Australia was established in 1977 when modern farming systems were starting to evolve. It ran until 1985.

The soil is a red brown earth –hard setting because of degradation by farming. The OC is 1% and Colwell P 54 (15 at 10-30cm and 4 at 20-30). The pH is 6.8 at surface but increases to 8.5 and 9 at depth. The growing season (Apr-Oct) rainfall is 355 mm.

The trial involved eight two year rotations, two tillage and 4 rates of N.
A Gross Margin analysis of the trial was completed in 1996 by Mike Krause.

The outstanding rotation was faba and wheat. Zero-tillage was introduced at year 11 Tillage and stubble systems had a small and inconsistent impact on wheat and pulse crop yields. A substantial increase in earthworm numbers occurred with zero-tillage.

Wheat following pulse crops with no N outyielded continuous wheat with high N. The main effect was root disease. The trial showed grain yields can be maintained in pulse wheat rotations.