Soil Structure and Fertility

The Key to Increasing Grain Production in the High Rainfall Zone

A report for

by Ben Morris

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Foreword

For the high rainfall zone to reach its full grain yield potential, the focus needs to be on soil structure and fertility. My farm is located in Toongabbie, Gippsland, Victoria. This falls within the defined area of 500 – 800 mm rainfall known as the high rainfall zone. We have long recognised that our soil is able to store summer rainfall for our winter crops. It is only in recent dry years that we have recognised how significantly valuable this is. With 40% of our rain falling outside our growing season, the more we can store and deliver in a dry winter growing season the higher our crop yield will be.

In many years water is not our most limiting factor. With good rotations, weed and disease control we are still not achieving our yield potential. The only factor left is fertility; our crops are not receiving enough of the nutrients required.

The aim of my research was to determine what we as farmers can do to improve our soil structure and fertility, and what nutrient levels are required to meet yield potentials of up to 8 tonne per hectare.

I believe that this research is most important for Gippsland where there is huge potential for expansion of the grain industry; however this research could have implications for the entire high rainfall zone of eastern Australia.

Supported by Nuffield Australia and my family and sponsored by Rural Finance I set off in July 2009 for 10 weeks to Kenya, England, Ireland, Canada, USA and New Zealand. This opportunity allowed me to see grain production under a range of climate extremes, from growing wheat on the equator to fields covered in snow for 5 months of the year. It also enabled me to visit researchers, agronomists and farmers to gain an understanding of how things like biology and chemistry effect soil and what we as farmers can do to manage our soils better.

In a nutshell what we need to do is...

- Zero Till
- Controlled Traffic

- Diverse crop rotations of summer and winter crops that include cereal and broadleaf types
- Raise our soil pH to above 6.0 (Water test)
- Explore new methods of controlling weeds that don't include burning, soil cultivation, grazing and hay cutting.
- Apply nutrient as required by our crops based on local trials.

Acknowledgments

To my wife Tanya and my children, Lachlan and Ryan who supported each other while their husband and father was overseas for 16 weeks.

My father Ian and brother Allister who kept an eye on things and kept the farm going while I was gone.

Rural Finance for their support, as without their sponsorship this once in a lifetime opportunity would not have been possible.

Thanks to Jonti Barclay, who organised my itinerary in Kenya, and opening his own farm and home to me.

Retired Prof Gordon Spoor from Silsoe Ag College and Prof Keith WT Goulding from Rothamstead Research Farm, who allowed me to see their research as well as organising some farm visits in England.

Nuffield International, who provided the opportunity and the network for an effective international study tour.

Brian and Jana Lindley from No Till on the Plains in Kansas, as well as Dwayne Beck from Dakota Lakes Research Farm in South Dakota, who together provided me with the opportunity to spend three weeks visiting leading farmers in the great plains of the USA.

To my Nuffield mates, who travelled with me for six weeks around the world; I have learnt so much from you, about farming, business and life in general. Thank you so much.

And finally thanks must go to Nuffield Australia, who has developed the program to what it is today. Without the Nuffield network and support, the task of travelling, seeking out answers and writing this report would be too overwhelming for me. I have learnt much more than just my chosen topic. As I progress in my farming career I will be forever indebted to the Nuffield organisation.

Executive Summary

Computer modelling has shown that large increases in grain yield are possible in the high rainfall zone through improved soil structure. At Sale in central Gippsland, differences in soil structure could account for up to 3 t/ha of wheat grain in any given year. If we could improve our soil structure to provide an unrestrained root zone for our crops then our average wheat yield could be equivalent to what was recently regarded as a bumper crop. Such yields can only be achieved with a higher level of fertility than was needed in the past.

With this in mind I applied for a Nuffield scholarship to visit farmers, researchers and agronomists from around the world. From these people I studied various farming systems including organic, biological, conservation agriculture, and conventional farming. I hoped to see many techniques including, but not limited to, green manure crops, deep ripping, mouldboard ploughing, minimum tillage, direct drill and zero till. I wondered if any of these techniques could really improve our soils or were they undertaken for other reasons. I also wanted to see alternative grain crop types that could have a beneficial effect on soil structure and fertility.

It soon became apparent that the only grain farming system that improved the soil is ‘conservation agriculture.’ The philosophy of conservation agriculture is to avoid tillage and to keep the ground covered with crop residues at all times. This has positive effects on soil microbes and worms, that work together to improve soil structure and fertility. This farming system is constantly evolving, and the current best practise is the use of zero-till disc openers.

Zero-till is not without its problems. These problems include soil compaction, pest and disease pressure, herbicide resistant weeds and residue management at seeding. Most of these problems were solved with stubble burning and tillage in other farming systems. In zero-till these problems can be overcome through controlled traffic, diverse crop rotations and new thinking on weed control.

Australia leads the world in controlled traffic farming, yet the adoption rate in Australia is still low. I believe that the lack of controlled traffic could be the reason for the reluctance for people to use zero-till disc openers.

Growing a diverse rotation is one of the most important keys to zero-till farming. By growing a summer crop you shift the growing season and can achieve a much greater level of weed control than by continuous winter cropping. These alternate crop types with their more vigorous root system also have a positive effect on soil structure. Growing a varied range of plant species allows each one to improve the soil in a different way. Legumes have long been known to provide disease control and build nitrogen levels, but their benefits are much greater than that. Legumes can extract nutrients that other plants leave behind. They also feed a range of microbes that work to improve soil structure. The highest yielding wheat crop in the world was grown after a crop of field peas.

The biggest threat to modern zero-till faming systems is herbicide resistant weeds. It is a common belief that weeds proliferate because their seeds are in the soil in high numbers. In actual fact many weed seeds lie dormant for many years, only germinating when conditions are right for them to grow. If we can keep soil conditions right for our crops but not right for our weeds then we may be able to gain some headway on this battle of herbicide resistance that we face.

To grow cereal yields approaching 8 t/ha, canola and pulse yields approaching 4 t/ha we need to increase our soil fertility. It seems apparent that having a good soil structure and a diverse rotation is more important on soil fertility than the numbers on a soil test. If a crop has access to more soil it may be able to extract more nutrients than a soil test might suggest. However there are a range of nutrients that are required to grow any crop and if those nutrients are not available then they will need to be supplied.

Most grain farmers in North America and Europe maintain their soil pH above 6.0 (H_2O). Having a pH between 6 and 7 will make most nutrients more available than they would be outside this range.

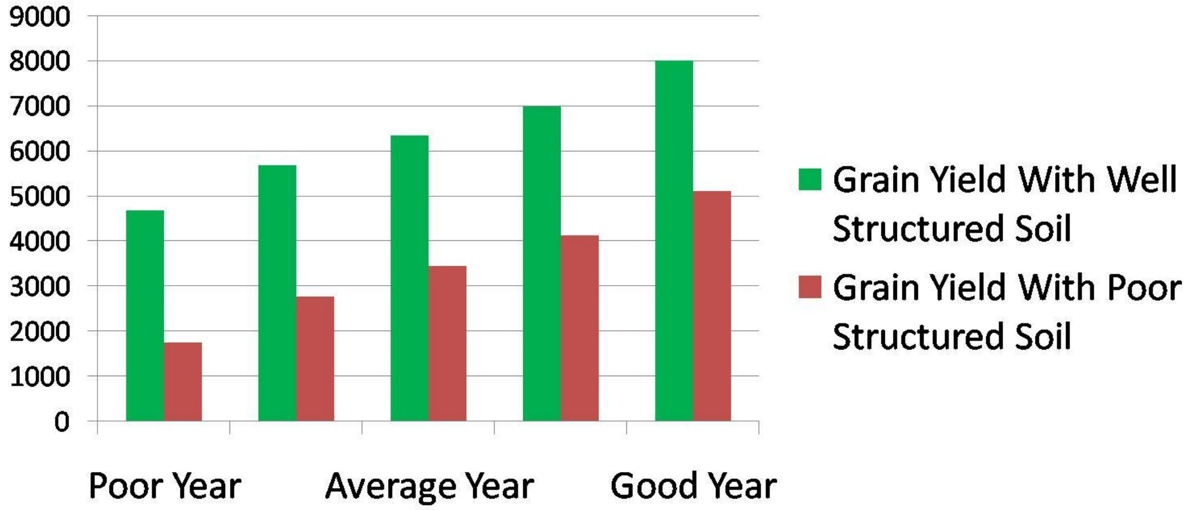
Recommendations

- Implement controlled traffic
- Research the limitations to the use of zero till disc seeders
- Grow a diverse rotation that includes summer and winter crops
- Maintain pH above 6.0 (H_2O)
- Ongoing research into nutrient availability
- Research into weeds.

Introduction

For the high rainfall zone to reach its full grain yield potential, the focus needs to be on soil structure and fertility.

In Central Gippsland 40% of our rain falls outside our winter crop growing season. The more water we can store from rain outside our growing season and deliver in a dry spring the higher our crop yield will be. The higher our water holding capacity, the better able we are to handle a wet winter and avoid water logging. This is demonstrated in the following chart which shows what wheat yields in Central Gippsland would be based on the ability of the soil type to store plant available water.



Source: “Subsoil constraints to cropping in the high rainfall zone”, DPI Victoria and GRDC
http://www.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/soil_mgmt_subsoil_high_rainfall?OpenDocument

In many years water is not our most limiting factor. With good rotations, weed and disease control we are still not achieving our yield potential. The only factor left is fertility; our crops are not receiving enough of the nutrients required. Also with potential wheat yields of 8 t/ha we will require an even higher level of fertility.

Objectives

As part of my study I wanted to visit farmers, researchers and agronomists. From these people I studied various farming systems including organic, biological, conservation agriculture, and conventional farming. I hoped to see many techniques including, but not limited to, green manure crops, deep ripping, mouldboard ploughing, minimum tillage, direct drill and zero till. I also wanted to see alternative grain crop types that could have a beneficial effect on soil structure and fertility.

The aim was to study these various techniques in a range of climate extremes and develop a perspective of which techniques could be suitable for our climate in the high rainfall zone.

Soil Science – a Brief Introduction

Soil science is not rocket science – it is much more complicated than that! It is beyond the scope of most people to understand everything that happens in a soil. Indeed scientists are discovering new things about soil all the time. What follows is only an insight into what goes on in the ground beneath our crops. Hopefully this will give the reader an appreciation of how important the practises undertaken by the farmer are to the long term sustainability and production of the land.

Biology

Earthworms are probably the most obvious organism that has positive benefits on grain production. Earthworms increase water infiltration and are important for recycling nutrients and building soil organic matter. Most people will understand that earthworms grow best where fertility is at its greatest and the soil is least disturbed. The biggest earthworms you will find in the garden are usually in an old overgrown garden bed that hasn't been dug for many years. Earthworms create tunnels through the soil that increase water infiltration. These tunnels are an engineering marvel when seen under a microscope, made up of plate like structures stacked around in circles to create a pipe like structure.

Vesicular arbuscular mycorrhizal fungi (VAM) are an extension to plant roots that make phosphorus and zinc available to the plant. Some crops are highly dependent on VAM and others have a low dependency. Some crops are non hosts and don't need VAM at all and will actually deplete the soil of VAM. Never grow a highly VAM dependant crop after a crop that is a non host or after a long fallow.

VAM dependency rankings of various crops				
Very High	High	Low	Very Low	VAM Non Hosts
Linseed	Sunflower	Fieldpea	Barley	Canola
Faba Bean	Soybean	Oats		Lupins
Cotton	Navy Bean	Wheat		
Maize	Mungbean	Triticale		
Pigeon Pea	Sorghum			
Lablab	Chickpea			

Source: Australian Grain Magazine, July-August 2009 http://www.ausgrain.com.au/Back%20Issues/192jagrn09/23_Mycorrhizae.pdf

Mycorrhizal fungi also produce a sticky substance known as glomalin. Glomalin is a recent discovery and has been referred to as 'soil glue.' Combined with the 'fungal ropes' this glue is responsible for building soil structure effectively binding minute soil particles together to create soil crumbs.

Most farmers are aware of the benefits of rhizobia. These nitrogen fixing bacteria live in nodules on the roots of legume plants. If a particular species of legume has not been grown in a paddock for some time then it is worthwhile inoculating the legume seed with the appropriate strain of rhizobia.

Other microbes in the soil are responsible for recycling nutrients and destroying disease causing pathogens. There is no end to the research and discoveries of soil life. It has often been said that there are more kilograms of life below the soil surface than there is above it.

A soil microbe researcher said that what is considered best practise agriculture is usually best practise for the soil microbes. These are things such as no-till, crop rotation, chemical rotation, integrated pest management, controlled traffic, maintaining correct pH and adequate fertility.

Chemistry

To understand what follows will require a basic knowledge of chemistry. To explain in any more detail is beyond the scope of this report.

All soils have what is known as a cation exchange capacity (CEC). This is the capacity of a soil to hold onto positively charged ions (cations). Cation exchange capacity is measured in millequivalents per 100 gram (meq). A soil that can hold 1 milligrams (mg) of hydrogen for every 100 gram of soil would have a meq of 1. This equates to 10 parts per million (ppm) of hydrogen. A list below shows the conversions for different cations.

- 1 meq/100g Hydrogen (H) = 10 ppm
- 1 meq/100g Sodium (Na) = 230 ppm
- 1 meq/100g Magnesium (Mg) =122 ppm
- 1 meq/100g Potassium (K) =391 ppm
- 1 meq/100g Calcium (Ca) =201 ppm
- 1 meq/100g Aluminium (Al) =90 ppm

Calcium and magnesium are important to flocculate the clay particles in the soil. Both of these elements carry two positive charges, this means that they can attach to two clay particles at the same time. Calcium holds the clay loosely together and magnesium holds the clay tightly together. This is why soils high in magnesium are prone to hard setting. There is a theory that you need a certain ratio of calcium and magnesium in your soil for maximum production. The proposed ratio (Ca:Mg) is somewhere between 7:1 and 3:1 depending on the cation exchange capacity (CEC) of the soil. Although there is some debate about the validity of these figures it is certainly apparent that if you are way outside the range then you will have problems. Trying to get the exact figure could be fraught with frustration.

Soils become acid because cations such as calcium, magnesium, sodium, potassium and most trace elements are removed by plant roots and replaced with hydrogen. This is the natural ‘exchange’ process that occurs in soils. When the plant dies and rots down these nutrients are once again exchanged back onto the soil and the soil then becomes less acid. Two things can affect this process. One is excessive rain that causes the nutrients to leach before they can attach to the soil; the second is nutrient removal from agricultural production. The solution is to grow deep rooted crops that prevent nutrient leaching and to replace nutrients that have been removed (calcium, magnesium and potassium) with lime, dolomite or potassium fertiliser. Once a soil become very acid, aluminium is released from inside the clay particles and becomes part of the cation exchange capacity. This aluminium has a toxic effect on root growth. The solution is to apply lime to correct the acidity allowing the aluminium to leach down through the soil where it won't be a problem.

Excess sodium usually results in a high pH (alkaline) soil. Sodium only has one positive charge, so it does nothing to hold clay together. You will often see very cloudy water in puddles or dams where the clay has high sodium content. The clay stays suspended in the water due to a small mass and high surface tension. Adding gypsum replaces the sodium with calcium, causing the clay to flocculate and therefore settle out of the water. When clay is wet in a high sodium soil it disperses and all the soil pores fill up with fine clay. Adding gypsum will cause the clay to flocculate and remove this problem.

The other ranges of elements that are essential for plant production are usually in the anion form. That is ions that have a negative charge. These are Phosphate, Nitrate, Sulphate and some trace elements. These anions are usually held within the soil organic matter. Sometimes they will bond with a cation making them less available. An example of this is Phosphate that can attach to aluminium, iron or calcium. This occurs when the pH is either too high (above 6.5) or too low (below 5.5), making these cations more available to be bonded to the phosphate. That is why maximum phosphate availability occurs between soil pH 5.5 and 6.5 (Water test). You can now understand why having a correct pH and high organic matter is so important to nutrient availability.

Physics

Let's us divide soil structure into three types, microstructure, macrostructure and pore structure.

Microstructure is affected by soil chemistry. As previously mentioned, high sodium content will cause dispersion and high magnesium will lead to hard setting soil. It has been suggested that having a good ratio of the basic cations will lead to good microstructure.
Suggested range of cations making up cec:

- Calcium 65 - 80%
- Magnesium 10 - 15%
- Potassium 1 - 5%
- Sodium 0 – 4%

- Aluminium 0 – 1%

Macrostructure is affected by soil organic matter. A soil low in organic matter will have poor aggregate stability and be prone to slaking, crusting and hard setting. A simple test is to place air dried soil aggregates (about the size of a pea) into some distilled water and observe what happens. If the aggregates float then the soil has excellent macrostructure. If the aggregates sink but do not fall apart then the macrostructure is good. If the aggregates sink and fall apart into smaller crumbs then the macrostructure is poor and organic matter needs improving. If the water becomes cloudy then the microstructure is poor and gypsum should be added.

Upper left tray contains high organic matter soil peds, lower left trays contain low organic matter soil peds. The trays on the right are the same soils submersed in water for several minutes demonstrating that organic matter prevents the soil from slaking. Note that there is no dispersion (cloudy water) as these soils are very high in calcium.

Pore structure is created by earthworms. Pore structure is destroyed by cultivation. Any practises that reduce or remove cultivation and compaction will allow earthworm numbers to increase. A good pore structure leads to good water infiltration.

Chemistry, physics and biology in the soil are all linked. Having good structure will allow the biology to grow which in turn helps to improve the chemistry leading to good structure. The cycle works in reverse also – good chemistry leads to good biology which improves the structure allowing the chemistry to correct itself.

A useful soil test kit can be made up from commonly available parts. This kit can be used to measure soil qualities such as biological activity, infiltration, bulk density, salinity, pH, nitrate, aggregate stability, slaking, earthworms and soil structure. The instructions for making and using this kit are available from the following website:
http://soils.usda.gov/SQI/assessment/test_kit.html

Arable Farming Systems

Conventional

Conventional farming in Australia is based on crops in rotation with pasture. A field is cropped for several years with repeated cultivations to break up compaction and to control weeds and root diseases. The field is then sown back to pasture to restore soil structure and organic matter. The pastures are grazed with either sheep or beef cattle to provide income and control weeds. These livestock are also used on crop stubbles during the fallow period to control weeds. This system of farming was held in high regard in the past as it was seen as sustainable and the livestock and cropping enterprises were seen as complimentary in many ways.

This system could possibly be sustainable in the long term if managed correctly. Cultivations should be timely and done at a slow speed to maintain soil structure as much as possible. Herbicide, insecticide and fungicide use was initially zero but as these tools became available farmers saw the value of them and the yield increases that followed.

In Australia’s climate of unreliable rainfall, conventional farming does not allow for maximum production as it does not provide the ideal in terms of soil structure and water infiltration. As farmer’s terms of trade have declined we need to maximise outputs and minimise inputs – conventional farming does not provide for this.

Organic

Consider the following statement from the International Federation of Organic Agriculture movements:

"Organic agriculture is a production system that sustains the health of soils, ecosystems and people. It relies on ecological processes, biodiversity and cycles adapted to local conditions, rather than the use of inputs with adverse effects. Organic agriculture combines tradition, innovation and science to benefit the shared environment and promote fair relationships and a good quality of life for all involved."

The statement actually makes quite a lot of sense and I believe is what most clear thinking farmers aspire to. The reality though is that organic farming is built on a belief system. Some Organic advocates believe that all herbicides, insecticides and fungicides are dangerous to human health. Others believe that chemical fertilisers are damaging to the soil biology. There is no central agreed definition of what organic agriculture is. It seems to me that organic food production is built on emotions and beliefs rather than clear science.

There are two reasons I see that a farmer might undertake organic food production. One is to cash in other peoples beliefs, the other is because of the farmers own beliefs. Organic farming generally replaces chemicals with cultivation placing no regard on having perfect soil structure and weed control. Researchers at Nafferton Experimental farm (managed by Newcastle University) in England have discovered that grain yield is half of what the best conventional farmers are achieving.

Biological

Biological farming is not the same as organic farming. The focus is on the soil biology and the benefits biology has on pest and disease control. Biological farmers aim to achieve a chemical balance in their soils that is ideal for soil microorganisms to live. They will avoid using any chemical fertiliser or pesticide that has an adverse effect on soil biology. The limited use of herbicides creates a greater need for soil cultivation to control weeds. This invariably does nothing for the soil structure, the very home of the microorganisms they are trying to protect.

Conservation Agriculture

Put a spade in the ground of a field that has been under no-till for 5 years or more and the first thing you will notice is how easily it goes in. The second thing that you notice is the number of earthworms and the pore structure that is present. Spending time with long term no-till farmers you begin to appreciate the quality of life and profitability they enjoy. You also notice that their machinery is up to date and they all have recently renovated or new houses. No-till brings prosperity back in to agriculture!

The conventional farming neighbour of a no-tiller doesn't believe the yields being achieved are possible. "Square Clouds" they say in Australia. Kenyan Farmers are accused of "Secret irrigation." In Tanzania they call it "Witchcraft." In England and North America it is respectively known as "Pub talk" and "Coffee shop talk."

My focus is going to be on zero-till farming, the culmination of an evolution in agriculture known as Conservation Agriculture.

Conservation Agriculture

Conservation Agriculture is a terminology that covers a range of farming systems that aim to conserve soil whilst maintaining or increasing production.

The traditional farming system in Australia involved several cultivations prior to sowing a crop. These cultivations were to break up soil compaction, control weeds and diseases and provide a seedbed for the crop. This system was generally rotated with pasture to provide a rest period and allow the soil structure and organic matter to recover.

The first phase in conservation agriculture is minimum tillage; one pass with a full cut to break up compaction and provide a seedbed prior to sowing. Stubble is retained if possible and weeds are controlled with herbicides. This system may allow continual cropping but it does not really allow the soil to fully recover.

The second phase is direct drilling. This technique combines the full cut cultivation with the sowing operation. The benefits of this is that soil is exposed to the elements for less time and that the tractor is not travelling on and re-compacting previously cultivated ground.

The third phase of conservation agriculture is no-till. In this system the only cultivation is with a knife point at sowing to break up compaction and root diseases below the seed. In self mulching soils or in a controlled traffic system a spear point can be used. In no-till all the residues are retained, however the sowing operation is still disturbing quite a bit of soil. This soil disturbance creates four problems. Firstly the residues are covered with soil which allows them to break down quicker. Second, the soil is opened up and soil water is lost through evaporation. Third, weed seeds are more likely to germinate either because they are now covered in soil (e.g. ryegrass) or exposed to light (e.g. wild radish). Fourth, soil biology performs best when there is no soil disturbance.

The latest phase of conservation agriculture is zero-till, which will be discussed next.

In conservation agriculture we need to consider what problems we covered up with cultivation. These are weeds, root diseases and soil compaction. Soil compaction can be alleviated with controlled traffic, diseases can be controlled with good rotations and weeds are generally controlled with herbicides.

There is growing concern about herbicide resistance with conservation agriculture. Rotations can be part of the solution for weed control, but new thinking is required if we are to combat what is the most significant threat to sustainable food production.

Many farmers say that no-till does not work on their soils. “We need to cultivate once every five years” is a common phrase. There are some soil type challenges. Silts and sandy soils in high rainfall/ low evaporation areas are quite prone to compaction. In these cases controlled traffic, possibly combined with drainage, will be the key to success. At the other end of the scale, heavy clays in dry areas are prone to cracking and drying. A mulch of cultivated soil is used to slow down this process. The key here is to retain crop residues as a mulch to prevent the soil from drying and cracking.

Another reason that farmers see a response from cultivation is that rotations are not doing their job of controlling root diseases. A farmer needs to ask whether the rotation is diverse enough, with a long enough break between similar crop types; or if the grass weed control in the broadleaf crops is adequate enough to prevent the carryover of root diseases.

The third reason that farmers may see a response from cultivation is that as soil carbon increases, an increasing amount of nutrient is tied up in organic matter. Cultivating will allow the organic matter to oxidise, releasing large amounts of nutrient and providing a significant crop response. As the organic matter stabilises this nutrient will be released slowly to the crop and you will begin to see the greater benefits of zero-till. It is well known that under the first few years of no-till nitrogen requirements will be greater.

Another problem is that of stratification. If an organic mat is building on the soil surface and not breaking down then there is most likely a biology problem. This could be caused by an extreme pH or a nutrient imbalance. The other type of stratification is that of individual nutrients. “We need to cultivate to mix the phosphorus into the soil” is a common phrase. Consider that some nutrients are immobile (e.g. phosphorus) and others are very mobile and prone to leaching (e.g. nitrogen, sulphur and potassium). It is no coincidence that plants take up immobile nutrients early in their growth when their roots are shallow and mobile nutrients in greater quantities as the plant increases in size and roots penetrate into deeper soil.

Never accept that no-till does not work. Work with your advisors to find out why it is not working and then correct that problem.

In summary, we need five things for conservation agriculture to work:

- Zero Till combined with 100% residue retention
- Controlled Traffic
- Good Rotations
- New thinking on weed control
- Adequate nutrition and correct soil pH.

Zero Till

Zero-till involves the use of a disc opener to place the seed in the soil with minimum disturbance. Most of the improvements from zero-till can be attributed to the retention of crop residues. The benefits of zero-till are as follows:

- Crop residues are retained on the surface where they can protect the soil from raindrop impact and wind, preventing crusting and wind erosion
- Crop residues are retained on the surface where they can protect the soil water from evaporation
- An increase in earthworms improves water infiltration leading to less run-off (less erosion) and less water logging
- An increase in soil biology responsible for nutrient cycling making nutrients more available to plants
- Weeds are least likely to germinate due to less soil disturbance and less access to light
- An increase in organic matter leads to greater water holding capacity, reducing the effects of drought and water logging.

Zero Till disc seeder, showing the residue handling capabilities

To understand the benefits of reduced evaporation consider the French-Schulz water use efficiency (WUE) model. Basically you tally up the rain that falls between crop sowing and maturity (known as growing season rain – GSR), add on any stored water that was present at sowing and then subtract anywhere from 90-130mm to allow for a water loss factor (WLF). Then you divide your grain yield in Kg by the total effective rainfall and you have water use efficiency. An example is shown below:

Growing season rainfall (GSR) = 220mm

Stored water = 70mm

WLF = 110mm

Wheat yield = 3000Kg/Ha

WUE=yield / (GSR + Stored water-WLF)

=3000 / (220+70-110)

=3000/180

=16.7 Kg/mm

The general recommendation is that with good management you should be able to achieve 15 Kg/mm for wheat, and that 20 Kg/mm is the best that you could achieve. However, over the last several seasons many leading no-till farmers have exceeded these figures. There are two reasons I see for this.

The first is that the figure of 20 Kg/mm was taken from a survey of trial plots in the 1980s and 20 Kg/mm was the best seen at that time. With better agronomy and newer varieties of wheat this figure should continually rise. I believe that farmers should always set their yield goals at 10-20% higher than what they have achieved in the same situation in the past – you will never hit higher than you aim.

The second reason is the water loss factor. Other than runoff and seepage water leaves soil in two ways, evaporation and transpiration collectively known as evapotranspiration (ET). Experienced zero-till farmers talk about removing the E from ET, which is eliminating the evaporation and only losing water through transpiration. They do this by maintaining a mulch of crop residues over their soil as much as they can. Zero-till farmers are always complaining that they can't grow enough residues; "Stubble is King" they say. It is not uncommon to hear of a WUE of 25Kg/mm with no or very little WLF.

Using the standard French-Schulz model the crop above that yielded 3 t/ha could have yielded 3.6 t/ha. With zero-till, it could have yielded 5.8 t/ha. Throw in increased infiltration and greater water holding capacity in the fallow period and you begin to see how it could be possible to achieve yields at double the current level. However, these yields will not be achieved overnight. Zero-till takes about five years before a soil depleted in organic matter starts to recover and earthworm numbers increase. It takes ten years before the full benefit becomes clear. There are reports of continual improvement even after 20 years. Adequate nutrition to meet these yields must also be supplied and this will be covered later in this report.

One of the biggest problems reported with disc planters is hair-pinning of crop residues at seeding. This is where crop residues are pushed into the ground at seeding time, rather than being cut by the disc, leaving the seed with little soil contact. Some farmers say that this is a problem for the first two years but then the soil has firmed up (firm, not compact); this provides a better surface for the disc to cut against. These farmers also replace their discs every season. Thinner discs are preferred over thicker ones as they maintain a sharper edge. The problem of hair-pinning is compounded by uneven spreading of residues by combine harvesters. Uneven spreading also contributes to uneven distribution of soil nutrients.

Canadian farmers will harvest on a different angle every year in an attempt to spread nutrients evenly. A quick flight in a plane and you will see that this is not achieving its objective. Also this doesn’t allow for controlled traffic. Many farmers in the plains of North America use Shelbourne stripper heads to harvest wheat as these only remove the grain and chaff leaving the straw remaining where it stands. Stripper heads work better in higher moisture situations with grain losses occurring in drier grain (below 12%). Corn heads remove the cobs and leave the stalks where they stand. An opportunity for machinery manufacturers is to develop some type of spreading mechanism that achieves a 100% even spread over the width of the header. If we can convey the crop from a width of up to 15m to a central point, then surely we can convey the residues the same width out from a central point.

Controlled Traffic

To understand the concept of controlled traffic, let’s first take a look at how compaction has affected the traditional farming practises in England.

After harvest crop residues are burnt to allow easy passage for machinery and to assist with disease control. The ground is then ploughed quite deeply to bury diseases and break up compaction created by machinery traffic. Following cultivations break the soil down further to create a seedbed for the following crop.

The recent ban on stubble burning for social and environmental reasons led to a change in farming systems. As burning for disease control is no longer an option more emphasis is placed on crop rotation. Wheat straw is now chopped and spread. A machine carrying discs and deep ripping tines is pulled through the soil to alleviate compaction and create a seedbed in one pass. Often canola seed is spread behind this machine and pressed into the soil with a roller. This one pass, cultivation-sowing operation is referred to as minimum tillage in England.

A farmer in England, who is keen to implement controlled traffic and no-till, observed that the only reason for the cultivation was to rectify the compaction caused by harvesting machinery, "The soil structure is best just before harvest because it has had 11 months of root growth to restore structure, then we go and compact it with combines and corn trucks" he said.

Australia leads the world in controlled traffic. This system is where all the wheels of machinery follow the same tracks. Wheel track widths are matched to a common size and so is implement width. Since grain harvesters are the hardest machines to modify, that is the perfect place to start. A typical harvester may have a wheel track width of 3m and a swath width of 9 or 12m. All other machinery is matched to this width or multiples of it. An example of this would be 9m harvester, 9m airseeder and a 27m boom spray. This means that only 10-15% of a paddock will be subject to compaction, the remainder never being compacted. The yield increase in the non compacted land and the cost saving more than make up for the reduced area farmed. This is not to mention the benefits of better timeliness of operations that this system of farming allows.

The problem in the UK is that it is very difficult to get wide machinery around on their narrow country roads. One farmer I saw followed a controlled traffic approach with his harvester on 3m centres and the rest of his machinery on 2m centres. Having now compacted 25% of his field he ran a deep ripper only on the compacted land. The whole field was then direct drilled with a shallow working narrow point. This farmer reported a yield increase in the wheel tracks of 40% from the ripping operation; this yield was still lower than the remaining non trafficked parts of his field.

Crop Rotation

One of the keys to success in any farming system is a good crop rotation. This is even more important in zero-till farming as we don't have the ability to burn residues and cultivate soil to control diseases. Many farmers report that their best wheat crop was grown after field peas. My family can testify to this, our best wheat was grown after peas. The current Guinness world record wheat crop of 15.637 t/ha (2010) was grown in a pea stubble as were the previous two world records of 15.363 (2007) and 15.015 t/ha (2003). These crops were all grown on the NZ South Island by Chris Dennison (15.015 t/ha) and Mike Solari (15.363 t/ha & 15.637 t/ha).

Simple two crop rotations have been quite successful in many areas. Two unrelated crops, usually a grass and a broadleaf, which grow well and have a good market, are grown in alternate years. Examples of these are wheat-peas, wheat-canola, and corn-soybeans. Most of these rotations are quite profitable for several years until nature catches up.

The corn-soybean rotation is a classic example. The corn beetle lays eggs in the corn that over-winter and hatch in time to attack the following corn crop. Growing soybeans in alternate years breaks this cycle and provides a relatively insect free corn crop in the following year. After two or three decades of this rotation, the corn beetle adapted to lay eggs that lay dormant for two winters, now able to attack the corn. The easy solution is an insecticide or a genetically modified crop that is able to fight off the insects.

Nature never has a monoculture or a fixed rotation. One plant will dominate an area for a period of time, and then as the fertility of the soil changes another plant will take over. In an area of annual plants some will dominate only for one year, others peak growth will occur in their second year, declining in the third and allowing a new species to take over.

It becomes apparent that the more diverse the rotation and the more unpredictable it is then the more sustainable it will be in the long term. The importance of rotations can be summed up by the following quote.

> *"The secret to no-till farming is crop rotation. Whenever you have a problem, try to see how you can solve it through rotation."* – Farmer, Oklahoma, USA

Annual grain crops can be divided into four types examples of which follow:

Cool season grasses

- Wheat
- Barley
- Triticale
- Oats
- Cereal Rye

Cool Season Broadleaf

- Canola
- Lupins
- Peas
- Faba Beans
- Lentils

Warm Season Grasses

- Corn
- Sorghum

Warm Season Broadleaf

- Soybeans
- Sunflower

Any rotation should aim to have at least one species from as many groups as possible. If you are only growing cool season crops then you should seriously consider growing a warm season crop. Most Australian farmers understand the benefits of rotating grass and broadleaf crops but are unaware of the benefits of including a summer crop in the rotation.

Reason for planting summer crops:

- Wet summers are a nuisance to winter crop harvest and perhaps we could turn a problem into an opportunity

- Growing summer crops shifts our growing season and confuses our pests and weeds reducing the opportunity for herbicide and pesticide resistance to take hold
- Summer crops have a different root system to winter crops and should have a beneficial effect on soil structure.

Other benefits of summer crops that may not have been expected

- Increase in crop intensity that uses up the extra water saved through no-till, especially in the high rainfall zone
- Better utilisation of machinery
- Better utilisation of labour and a more even workload
- Cash flow spread more evenly throughout the year
- There will more likely be something worthwhile to harvest every year
- More grain per hectare greater profitability.

In the high rainfall zone raised beds have been introduced to remove excess water to control water logging. This water logging has occurred either because the water holding capacity of the soil is not adequate to hold the winter rain and save it for grain fill in the spring or because the rotation is not intense enough to use up all the water that is available to the crop.

Dwayne Beck from Dakota Lakes Research Farm at Bismarck in North Dakota, USA, has developed a formula for calculating the intensity of any rotation. Basically any cool season crop is allocated one point and any warm season crop is allocated two points. Over the period of the rotation all the points are tallied up and then divided by the number of years. An example is where a cool season crop is grown every year. This would have an intensity of 1. If a cool season crop is rotated with a warm season crop but still only growing one crop per year then the intensity would be 1.5. A warm season crop every year would have an intensity of 2. Double cropping, with 2 warm season crops and two cool season crops over a three year period would still have an intensity of 2 but involves greater diversity. Growing a cool season and a warm season crop every year would have an intensity of 3, and growing two warm season crops in one year (possible in the tropics) would have an intensity of 4.

Farmers in the drier areas of Oklahoma and Kansas traditionally only grew cool season crops. Zero-till was introduced to combat soil erosion. The moisture retained from zero-till allowed them to grow warm season crops such as soybeans & corn in the wetter areas, and sorghum and sunflowers in the drier areas. This new system of farming has allowed them to grow on average 1.5 crops per year, taking their rotation intensity from 1 to 2.5. One farmer reported that in comparing a twelve year rotation he grew 18 crops compared to twelve and a total harvest of more than twice as many bushels.

Zero Till has allowed the expansion of summer crops such as corn (maize) in the drier regions of USA.

Different root systems have different effects on the soil. Some plants have fine roots, others coarse, some have deep roots, others shallow. Some roots are high in carbon, others are high in nitrogen. Different root systems support different types of biology. All plants will improve the soil structure and fertility in different ways. Some plants will bring up nutrients that have been lost deep in the soil. As the residues of these plants break down they supply the nutrients to the next crop. Many farmers report an increase in their wheat yields after they began to grow corn, often achieving yields that had never been achieved before. This is most likely a response to an improved soil structure and greater water holding capacity. One farmer from North Dakota says that his better wheat crops always follow peas, but his best wheat yields are where those peas were grown after corn. He believes that the high carbon root system of the corn compliments the high nitrogen root system of the peas, having phenomenal effects on the soil structure, fertility and biology.

Often a stacked rotation can have an advantage. A stacked rotation is where the same crop is grown two years in a row. An example is two crops of corn. Although the second crop will never yield as well as the first it allows for a greater amount of residual herbicide to be used in the first crop. This leads to a higher level of weed control and possibly a lower production cost in the second year.

Another example of a stacked rotation is two crops of soybeans. The first crop in inoculated with the correct rhizobia. These bacteria build up in numbers as the soybeans grow. The following crop of soybeans has access to a greater number of bacteria than a farmer could ever provide out of a packet, and will often out yield the first crop. Proponents of stacked rotations say that diseases aren't a big issue if there has been an adequate break before the first crop was grown.

With approximately 85% of Australia's grain area sown to winter cereals it is time for Australian farmers to consider how they can diversify their rotations.

Cover Crops

Cover crops (also called catch crops) will often be used where there are limitations on growing diverse rotations. Where seasonal conditions do not favour the growing of a cool season broadleaf profitably then something such as mustard or a legume could be planted to recycle nutrients, produce nitrogen, use up moisture and provide diversity in the rotation. This crop will be grown between summer crops and then sprayed out before maturity and kept as mulch. The effects of disease and weed control, as well as nutrient supply make this a worthwhile proposition in many cases.

A similar technique could be used where summers are too hot and dry to grow warm season crops. Sorghum, millet, soybeans or sunflowers (or a combination of any of these) could be planted after winter crop harvest to provide groundcover and diversity. This same mix of crops could be planted in the spring as a replacement for a winter crop. This might be considered where a fallow period would be used for weed control.

Most farmers would agree that it makes much more sense to grow a crop that is harvested for grain rather than a cover crop. If this is possible then it makes financial sense. If a grain crop is destined to fail because of drought then it might make sense to sacrifice that crop before maturity and use it as a cover crop. This will have many benefits in regard to weed control, allowing a knockdown spray to be used on weeds before they set seed. The groundcover provided by a standing wheat crop in a drought year is much greater than the same crop that has been harvested for grain or hay. It is a financial hurdle to overcome in a drought; however the benefits for the next crop need to be compared to the small financial gains of harvesting very light crops.

The immediate financial implications of cover crops need to be weighed up against the long term sustainability of agriculture. One farmer who is very keen on cover crops says that he likes to have something growing all the time. He uses a knockdown herbicide on a cover crop to plant his next grain crop, not allowing an opportunity for weeds to become established. He says that he doesn't use any selective herbicides, and that his fertiliser bill is greatly reduced because of the nutrient recycling that occurs. As soon as he has harvested a grain crop he will plant another cover crop.

One problem that Australian farmers see with cover crops is that they use moisture that would be available for the next crop. Cover crop advocates say that the mulch provided by a cover crop reduces evaporation so much; and the nutrient recycling is so efficient that this makes up for the reduction in stored water. We need some research in Australian conditions to quantify this. We should not turn our backs on cover crops as they may be the key to controlling weeds in the future and could be the next revolution in agriculture.

New thinking on weed control

Most people agree that weed control is a numbers game. If we can reduce or eliminate our seed-bank, then we won't have a weed problem. This is generally correct but not always true. Some weeds can have a great crop of seeds but then these seeds don't germinate because conditions are not right.

Chaff carts have been used in some places to collect herbicide resistant annual ryegrass seed from the back of the combine harvester and remove it from the field. These farmers report that after a few years ryegrass is at such low numbers that it is not a problem.

One farmer in Western Australia developed a concept where a big square baler is towed behind a combine harvester. A belt conveys all the straw, chaff and weed seeds to the baler, where they are baled and removed from the field. In using this technique for a number of years they have virtually eliminated their ryegrass problem. However removing all the residues is not desirable. I would imagine that all that bare ground would be ideal for broadleaf weeds to flourish.

Perhaps someone who is innovative could invent a machine that combine residue spreading with seed destruction. I have often wondered if ryegrass could be milled, ground, etc so that it wouldn't germinate.

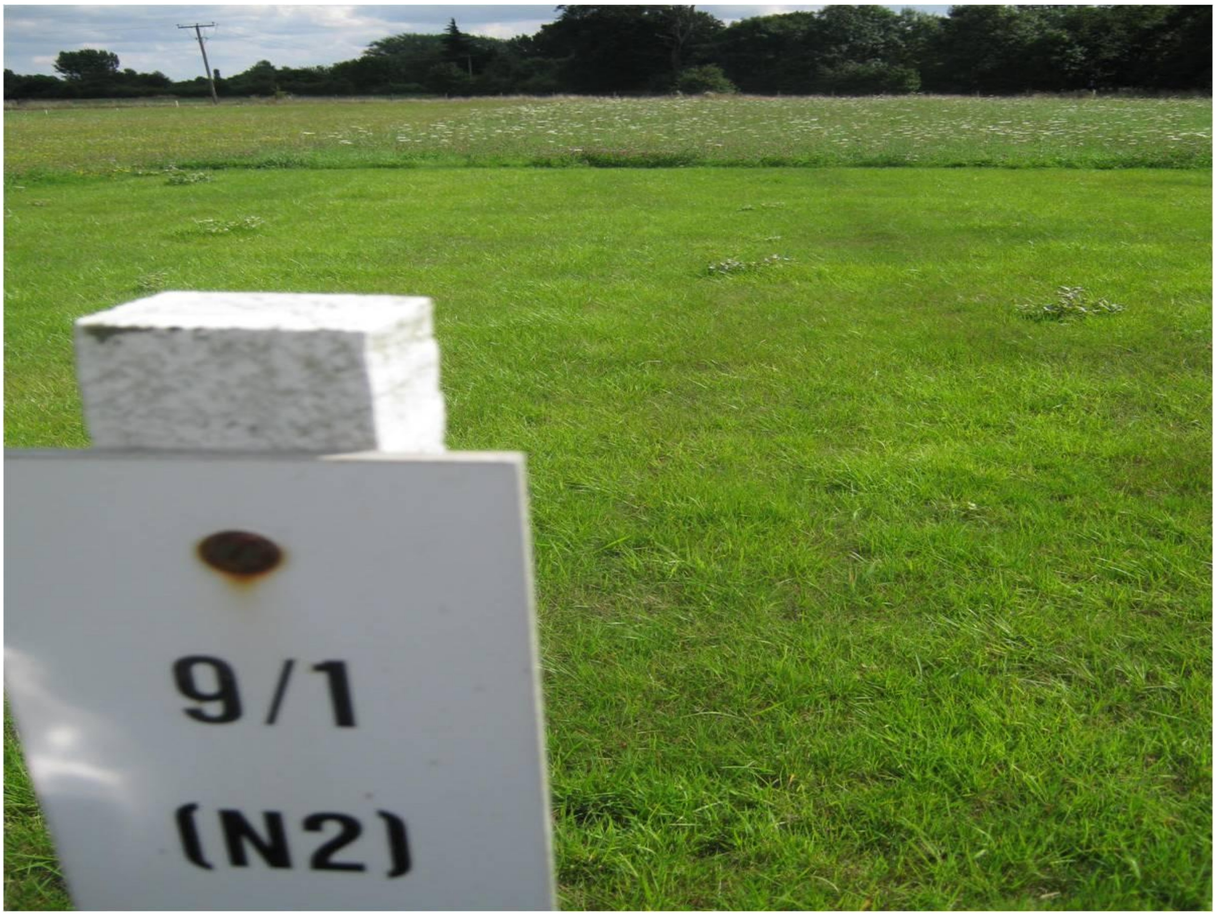
Annual ryegrass seems to thrive in compacted soils with low organic matter. It is no coincidence that its root system is ideal to restore these soils. It germinates freely where there is good seed to soil contact, a condition that coincides with the previously mentioned soil. Is it possible that a good structured surface soil high in organic matter will inhibit the germination of annual ryegrass seeds?

I had a neighbour whose farm was originally a wheat farm. It had been under irrigated perennial pasture for several decades and all the traditional cropping weeds were no longer growing at all. He cut the grass along the roadside regularly and began knockdown spraying the fence-line to keep it looking tidy. After some time wild radish began to appear, ten years later he had a neat little hedge of wild radish. I always believed that wild radish germinated because we cultivated the soil. I am now convinced that it germinates because of bare ground.

It has been said that wild radish will germinate after a flash of sunlight. Have you ever noticed how quickly broadleaf weeds cover bare soil and protect it from the elements?

One will often see old stockyards that are covered in weeds. The simple conclusion is that the weeds came with the manure that the stock left behind. Why is it that one pen will be covered in marshmallow, another in stinging nettles and yet another will have some type of weed that is six feet tall and produces a million seeds blowing around everywhere, but only growing in that pen? The answer is that all these weeds are responding to different levels of fertility.

There is an experiment at Rothamsted Research in England known as the Park Grass Experiment. In this experiment each plot is fertilised differently and maintained at a different pH. The treatments have continued for several decades providing vastly different fertility levels. The entire field is cut for hay every year with the hay removed. One glance will show the obvious differences in vegetation between the plots. Every plant on this planet grows best in a different soil condition.



"Park Grass" experiment at Rothamstead Research Farm, England. The plot at the bottom of the photo has a much lower pH than the plot above which contains greater diversity. This experiment clearly demonstrates that plant species are affected differently by soil chemistry.

We need research into what causes different weed species to flourish and what are the triggers to germination. We know more about some species of endangered animals that provide no benefit to man than we do about the weeds that are the biggest threat to sustainable food production.

Soil pH and Fertility

If we are going to use plants to improve our soil structure then we need those plants to grow at their maximum potential. As we improve our soil structure then we are going to achieve greater yield potential which will require a greater level of fertility.

Just as a chain is as strong as its weakest link, the most important nutrient is the one that is the most limiting to production. The German scientist, Liebig, summed this up with his law of the minimum. Along with Carbon (C), Hydrogen (H) and Oxygen (O), which are found in carbon dioxide and water, there are thirteen chemical elements that are found in plants and necessary for production. These are Nitrogen (N), Phosphorus (P), Potassium (K), Sulphur (S), Calcium (Ca), Magnesium (Mg), Sodium (Na), Copper (Cu), Zinc (Zn), Molybdenum (Mo), Boron (B), Manganese (Mn), and Iron (Fe). Any one of these could be a limiting factor.

It would require a book of many chapters to explain all the interactions and relationships between the different chemical elements in the soil and what makes each one available or unavailable. Indeed these books are available and I would recommend that farmers seek out something that is written at a level that they can understand and enjoy reading.

As far as soil tests go, each laboratory may use a slightly different testing method. As long as the testing methods are done to a recognised standard I would say that any laboratory is ok, just make sure you use the same one all the time. Soil testing should be followed up with tissue testing and visual inspection for nutrient deficiencies as well as on farm trials to see that fertiliser or foliar applications are achieving the desired results.

What follows is a very brief guide as to where to begin. I can only advise that farmers need to work with their advisers to try to understand what works in their soil types. As time goes on and nutrient deficiencies are overcome new ones will crop up. This should be seen as a positive because you are moving on to a higher level of production.

Soil pH, Calcium (Ca) and Magnesium (Mg)

It is often quoted that the ideal soil pH is about 6.5 (note that all the pHs quoted here are based on the water test, to convert to the CaCl test, subtract 1.) The reason for this figure is that most nutrients are freely available at this pH. In England where wheat yields of 12 t/ha are regularly achieved, farmers do not let their pH fall below 6.0. Some have soils that are naturally high in lime and the pH may be 8.0 or above. At this level most nutrients are still available and those that aren't are applied as a foliar spray. There is not much that can be done to lower a soil pH, however some farmers report that the introduction of no-till has allowed the pH to drop naturally to a neutral (7.0) or slightly acid (6.5) level.

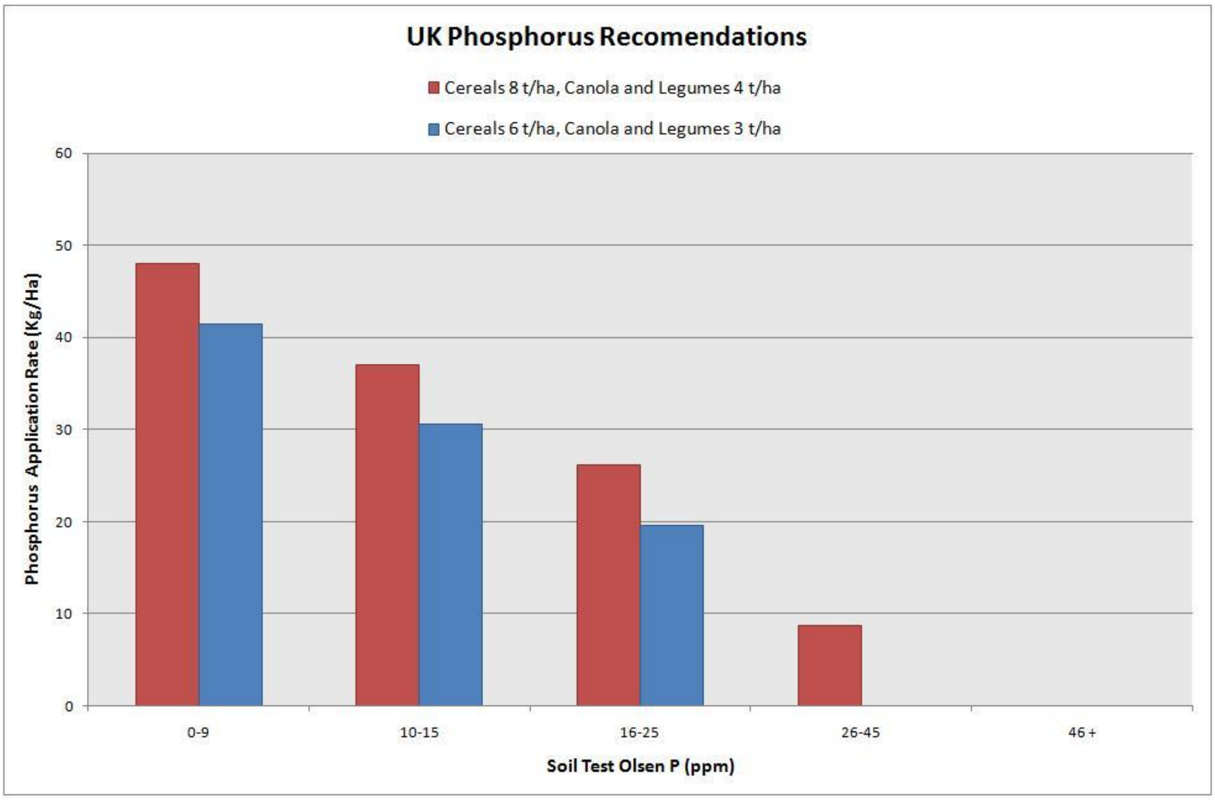
If your soil is acid you need lime (calcium carbonate). A pretty simple answer really. The question is what type of lime. If your soil is low in magnesium you need a high magnesium lime or dolomite (magnesium carbonate) If your soil is high in magnesium you need a low or zero magnesium lime. The carbonates in these limes react with the hydrogen (acid) in the soil and replace this with calcium or magnesium.

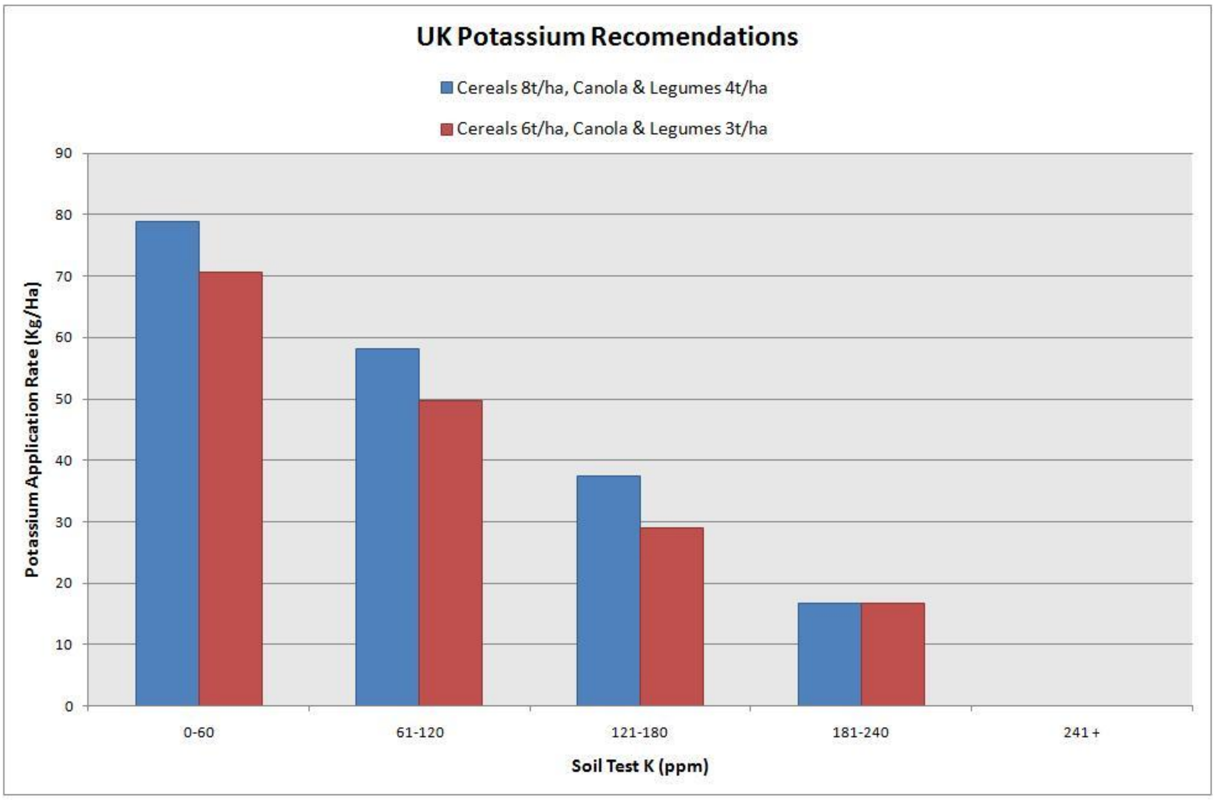
Some Australian soils are so low in Calcium that calcium deficiency may occur. It follows that an acid, calcium deficient soil needs lime. An alkaline soil that is deficient in calcium needs gypsum (calcium sulphate). This soil is usually high in sodium or magnesium. The sulphate in gypsum will help to shed these elements and replace them with calcium.

N, P, K and S

Nitrogen, Phosphorus, Potassium and Sulphur are known as the major elements because they are required in the greatest amount. There has been much work done on these elements and it is worth seeking local knowledge as regards to soil tests and what type of fertiliser to use in local conditions. As with any element, if you are deficient in one of the major elements you need to correct that deficiency. Sometimes a response to a particular fertiliser is not found even when the theory suggests that it should. Either try another form of the same nutrient or accept the fact that that nutrient is not the most limiting and try something else.

Below are two charts that show the United Kingdom recommendation for potassium and phosphorus. These may be a useful starting point for the high rainfall zone of Australia.





Information sourced from “Fertiliser Recommendations” - Ministry of Agriculture, Fisheries and Food, London.

Trace Elements

Farmers need to work with their advisers to develop a trace element program for their soil types and cropping program. Trace elements can be applied foliar but it may take up to four applications to achieve the desired result. The ideal would be to build up the levels of these in the soil so that the plant can access all it needs that way.

Some trace elements will not be available even when present in the soil. This is because the pH is either too high or too low. After correcting the pH this should not be an issue. In the meantime foliar applications will be necessary to achieve maximum production.

Recommendations

- Farmers should work towards implementing controlled traffic. There are recognised machinery standards that will make this process easier. Visit the Australian Controlled Traffic Farming Association Website for further information. www.actfa.net/
- Farmers using No-Till techniques should consider using Zero-Till disc seeders. Research on the limitations of these machines needs to be undertaken and/or quantified. Farmers should join their state No-Till organisation for the support that these organisations provide in their changing farming systems.
- Begin growing summer crops in the high rainfall zone. Consider taking a problem paddock out of production for one winter growing season and planting a summer crop that spring. There are a number of farmers in Southern Australia doing this. Visit my Website or contact me for further information. http://southerncorn.blogspot.com/
- Use lime to raise soil pH above 6.0 (H_2O). Australian farmers and advisors have been too slow to realise the problems associated with acid soils.
- Research into the usefulness of cover crops. This could be part of the next revolution in grain production and Australia does not want to be left behind.
- Ongoing research into nutrient availability. The rules keep changing here and we need to update our knowledge to keep up.
- Research into weeds. Weeds are the biggest threat to conservation agriculture and we need to be on top of them at all times.

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Plain English Compendium Summary

Project Title:	Soil Structure and Fertility
Nuffield Australia Project No.:	0909
Scholar:	Ben Morris
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Objectives	The aim of my research was to identify techniques farmers could use to improve their soil structure and fertility, so that they can grow higher yielding crops of greater quality
Background	The high rainfall grain production zone of Australia is not achieving its yield potential. It has been identified that soil structure and fertility are major contributing factors.
Research	Practical research was undertaken by visiting research farms and laboratories around the world and identifying techniques they have developed to improve soil structure and fertility. These techniques were tested further by visiting farms and seeing firsthand the results of these techniques.
Outcomes	The outcomes of this research are presented in this report and will be followed up by trials on my own farm and a public trial site within my region as well as gradual implementation of proven techniques. Briefly these techniques are zero-till, controlled traffic, diverse rotations and getting the basics right in soil pH and fertility.
Implications	It is hoped that I can inspire other farmers to implement some of these techniques and for researchers to undertake the research that I have identified as being important.