Improving Soil Health with Manure and Cover Crops

A report for

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Executive Summary

Currently, most agricultural soils do not have the capacity to sustain continuous cropping and high yield production, without depending on expensive synthetic inputs. Agricultural practices have become simplified with large scale mono-cropping and very little diversity in rotations being common. The main reason for this study was to investigate how to improve soil health, water holding capacity and water use efficiency with manure and crop diversity. This is important for all producers, to enable ongoing profitability amidst declining terms of trade in agriculture. The major findings of this study indicate that soils need more carbon. A cropping system that creates a favourable soil habitat for microbes, that includes opportunist cover crops maximising photosynthesis, is the key to building carbon and building healthy soil. Cash crop residues alone, especially legumes will not significantly build carbon.

In addition, the supply of water and nutrients to plants is biologically driven, and as such, increasing water holding capacity and water use efficiency of soils requires more carbon and more soil biota. Soil microbes create soil aggregation and cycle nutrients, which allows more water to be stored in the soil and more nutrient availability to plants.

Grain producers need a better understanding of how the soil food web functions, and continued investigation is necessary into what impacts current farming practices, including the use of synthetic fertilisers, herbicides, fungicides, seed dressings and insecticides are having on the soil food web.

Soil cover is critical to soil health and improving water use efficiency. Protecting the soil with residue and living plants provides food for microbes and helps reduce evaporation, soil temperature and erosion.

Manure and compost are beneficial additions to soil, significantly less harmful to soil biota than synthetic fertilisers, and can improve the water holding capacity and structure of soils. However, their addition alone will not significantly increase soil organic carbon. Manure, when spread in a no-tillage system is best applied into a living cover crop in cool weather for maximum nitrogen use efficiency.

Table of Contents

Table of Figures

List of Tables

Foreword

I would consider our farm to be a very sustainable, profitable business. Since 1877 when my ancestors began farming on Yorke Peninsula in South Australia, our farm has continued to evolve; changing from wheat-sheep-fallow rotation to a continuous cropping system. Significant production gains have come from no-till, integrating pulses, adopting precision technology, auto-steer, yield mapping, stubble retention and controlled traffic. We currently own and operate two properties totalling 7,000 hectares (ha) on Yorke Peninsula and Kangaroo Island. We now use poultry manure as the primary nutrition source for crop production on Yorke Peninsula instead of synthetic fertilisers. We store, process, market and export our own grain produced on Kangaroo Island. We have leveraged our equity, buying and developing land regularly to allow future generations the opportunity to continue farming profitably.

Despite our best efforts to increase productivity to feed an increasing population, we face increasing regulatory and environmental pressure on farming practices. Consumers are increasingly demanding safe, nutritional, traceable food production. The terms of trade in broadacre agriculture are consistently decreasing. The nutrient value of the food produced is consistently declining, but there is a need to produce nutritious food, and that is produced from healthy soil. Future generations cannot simply apply more expensive synthetic fertilisers and chemicals to increase production and expect to remain profitable.

Farming has become too simplistic. There must be a regenerative approach to farming in the future.

I am a fifth-generation farmer so my family must have been farming sustainably over the years – or have we? Why has it been necessary for each generation to farm significantly more land to maintain profitability? In my opinion, it is unlikely that utilising current grain production systems will result in any reprieve from declining terms of trade in agriculture.

Research on our farm over the last three years has shown no detriment to winter grain yield or quality following a multi-species summer cover crop, terminated at flowering. There is also evidence of an improvement in water use efficiency (WUE) over the last 15 years due to the annual addition of 2.5t/ha chicken manure as a replacement to any synthetic starter fertiliser. Soils can capture, maintain and utilise more carbon and water than currently accessible.

It is for this reason I feel that we need to reflect, understand and change the way in which we farm if we are to be truly sustainable into the future.

My Nuffield scholarship gave me the opportunity to learn from others, to gain insight into production systems that are more resilient and ultimately more profitable than that which we are currently implementing.

Over a period extending eight months I have travelled to nine countries (Netherlands, Ireland, United States, Canada, Mexico, Brazil, France, United Kingdom, and New Zealand) and visited many types of agricultural industries. I have had the privilege of travelling with and meeting entrepreneurs, farmers, researchers and successful business owners all over the world. It has been a very humbling experience. The generosity I have been shown in my travels has been overwhelming.

I feel so privileged to have been given this opportunity and to have met so many great people. I have enjoyed it immensely and I am extremely grateful. None of this would have been possible without the support of Nuffield Australia and my investor Nufarm Australia.

Acknowledgements

Firstly, I want to thank my wife Jodie for supporting my decision to undertake this Nuffield journey. Being away from my family for four months was very difficult for me and for my wife and three children. Without the love, support and blessing of my wife I could not have participated in such a program.

Secondly, I want to thank my brother Ben, my parents and our excellent staff who have taken on more responsibility and worked tirelessly to ensure the ongoing productivity and profitability of our business in my absence.

I would also like to thank all the people that have given their time to meet with me, feed and accommodate me overseas whilst on my travels. I have formed many friendships and feel extremely fortunate to have met so many generous, inspiring people around the world.

I am also extremely grateful to Nuffield Australia for placing its faith in me and giving me this incredible opportunity to travel, to learn and to meet so many incredible people along the way.

Finally, I want to thank Nufarm Australia for investing in me. I am forever grateful for your foresight and continued investment in agriculture in Australia.

Abbreviations

AMF	Arbuscular mycorrhizal fungi
C	Carbon
CEC	Cation Exchange Capacity
CO_2	Carbon dioxide
DAP	Di-ammonium Phosphate
°C	Degrees Celsius
GRDC	Grains Research and Development Corporation
Ha	Hectare
N	Nitrogen
NO_2	Nitrogen dioxide
NH_4	Ammonia
NUE	Nitrogen Use Efficiency
OC	Organic Carbon
P	Phosphorus
PAW	Plant Available Water
RA	Regenerative Agriculture
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SFW	Soil Food Web
t/ha	Tonnes per Hectare
UK	United Kingdom
USA	United States of America
WHC	Water Holding Capacity
WUE	Water Use Efficiency

Objectives

This report sets out to investigate the ability to improve soil health and profitability in dryland grain producing regions of South Australia, by answering the following questions:

1. How to significantly increase soil organic carbon?
2. What role does biology have in soil health?
3. Are cover crops a viable option in low rainfall areas of South Australia?
4. Is it possible to keep soil biology alive over a hot, dry summer?
5. How to use and apply manure more efficiently in a no-till cropping system?

Chapter 1: Introduction

Southern cropping regions of South Australia typically receive 300-600mm of rainfall annually. The annual crops are typically sown in April/May, grown between June and October, and harvested in November/December. Approximately 75% of annual rainfall occurs during the growing season. Rotations are typically cereal-legume-cereal. Most crops are planted no-till (knife point/press wheel, or disc) and in most cases crop residues are returned to the soil.

Over the last 20 years there has been significant improvement to soil structure and water infiltration from decreased tillage. Since crop residues have been retained in no-till systems, there has been significantly less water and wind erosion. However, the increase of organic carbon in these soils has been minimal. The use of synthetic fertilisers and chemicals has increased. Most livestock have been removed from farms in favour of cropping due to increasing land prices. Crop diversity in this rainfall zone is currently very limited.

This trend is not isolated to South Australian farms. There are many soils around the world which are still being degraded and are unprofitable, currently viable only through government subsidy programs. Monocultures and a lack of diversity have created systems which require large amounts of expensive seed, chemical and synthetic fertiliser inputs to produce a crop.

"*There is no system of production, or soil amendment that will fix what is wrong with your soil. Only an understanding of how the soil functions will fix what ails your soil*" (Stika, 2016).

The difference between sustainable agriculture and regenerative agriculture

Sustainable agriculture is farming in sustainable ways, meeting society's food and textile needs in the present without compromising the ability of future generations to meet their own needs (Agricultural Sustainability Institute, 2019). Sustainable agriculture needs to be sustainable environmentally, socially and economically. It is maintaining a profitable system of production. How sustainable are current farming systems considering increasing production costs, commercial fertiliser and chemical, irrigation water availability and static grain prices?

Regenerative Agriculture (RA) is an approach to food and farming systems that aims to regenerate topsoil, increase biodiversity, improve water cycles and increase resilience to climate fluctuation (Terra Genesis International, 2018). RA is about improving crop production systems to restore soil health. Understanding how the soil food web (SFW) works and what it needs to flourish is the first step to improved profitability and true sustainability.

The keys to restoring soil health are:

- Minimise soil disturbance
- Maintain soil cover at all times
- Maintain living roots as much as possible
- More plant diversity
- Feed soils – organisms need energy
- Minimise use of chemicals/ synthetics
- Incorporate animals (Dan Kittredge, pers. comm., 2018)

"*Soils are living ecosystems, soil is not dirt; it is alive*" (Stika, 2016).

Chapter 2: Soil Carbon

The most limiting element in the soil for crop production is carbon. So much emphasis in current cropping systems is placed on the need for nitrogen and phosphorus additions with little regard for carbon. Rebuilding soils is more than no-till and stubble retention, it is adding carbon. Altering current management systems will be required to store additional carbon (Baldock, 2008).

> "*You are not dry; you are just short on carbon. If you have more carbon entering the soil than leaving, your children will likely farm your land; if you have more carbon leaving than entering, they likely won't*" (Fuhrer, 2018).

Soil organic carbon (SOC) is the measurable carbon component of organic compounds in soil organic matter (SOM) (Griffin, Hoyle & Murphy, 2013). As SOM increases from 1% by weight to 3% by weight, the water holding capacity (WHC) of the soil doubles. 95% of the nitrogen and over 50% of the phosphorous in the soil is contained in SOM (Stika, 2016).

SOM has three functions in the soil (See Figure 1):

- **Biological:** SOM is a key food source for soil biology. In turn these soil organisms produce glues called glomalin that hold the soil together in aggregates improving the structural stability of the soil. This fraction of organic matter is the most fragile and is easily lost, reducing the capacity of the soil to infiltrate and retain water. Increasing the carbon content of the soil and reducing tillage maintains these glues and soil aggregation.
- **Physical**: SOM promotes good soil structure. Good soil aggregation will resist compaction and erosion, and plant roots will require less energy to search for water and nutrients, ultimately improving the WHC and water use efficiency (WUE) of the soil.
- **Chemical**: SOM serves as a source of nutrients, mainly nitrogen and phosphorus required for plant growth. It also increases the buffering and exchange capacity of soils (Weber, 1996).

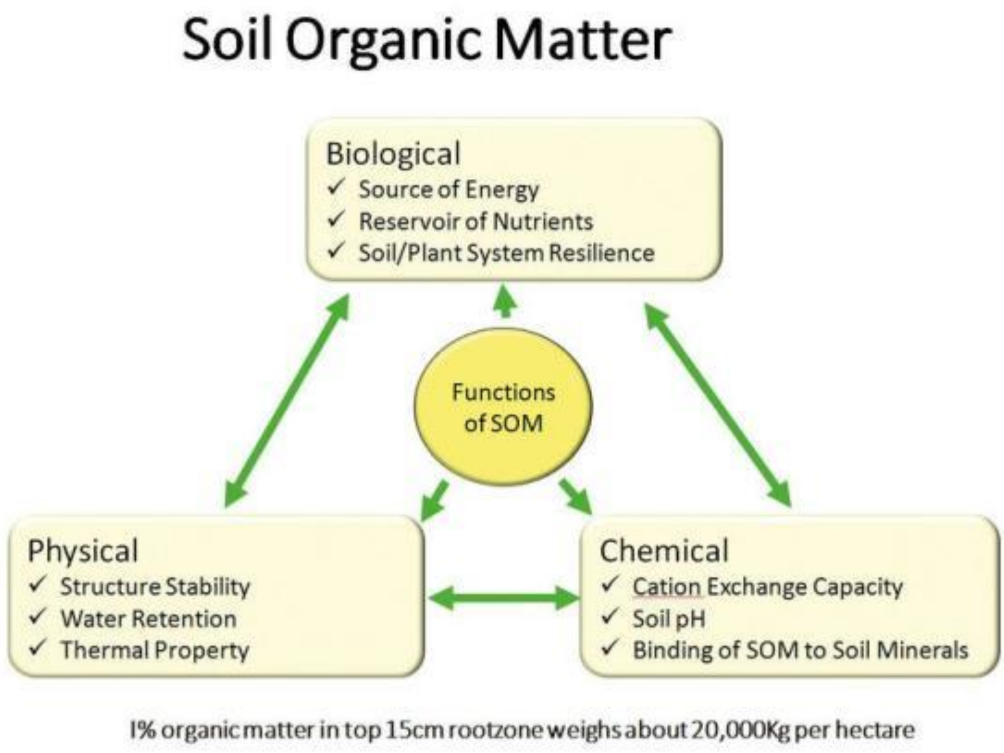

Figure 1: Functions of SOM (Ward, 2014).

So why is SOC so important in agricultural production systems?

- Higher SOC improves the resilience of soil and plants to disease, pests, drought and compaction.
- Increasing SOC leads to better WHC, better water infiltration and extraction, as well as better nutrient extraction and utilisation.

Some soils in France and Brazil have shown that within a managed pasture, SOC can be built at a rate of 1% per year. This has been achieved with continuous perennial roots and high crop diversity in high rainfall areas, so long as no synthetic fertiliser or chemicals were applied (Ademir Calegari, pers. comm., 2018).

In grain production systems SOC has been shown to increase at a rate of 0.1% per year with the use of compost application, cover crops and no-till practices. Steve Groff (pers. comm. 2018) from Pennsylvania, USA, has improved his SOC by 3% over the last 30 years by utilising these practices (in a high rainfall area - 900mm/year).

Plants take in carbon dioxide (CO_2) from the atmosphere through photosynthesis. This captured carbon is exuded through the plant roots and into the soil. In grain crops, carbon held in the plant is distributed relatively evenly between the grain, the residue and the roots (Fuhrer, 2018). With a third of the carbon being removed in the form of grain, and another third if residues are baled or burnt, building SOC in annual cropping systems is a challenge. In tillage systems it is even more difficult. The disruption and aeration of the soil through tillage results in organic matter and therefore SOC, being consumed at a faster rate than it is produced (Stika, 2016).

Crop nutrient cycling and maintaining adequate soil cover depends on the composition of the residue. The Carbon:Nitrogen (C:N) ratio of different plants is important when considering a crop rotation which will feed the soil microbes and supply armour to the soil (See Figure 2).

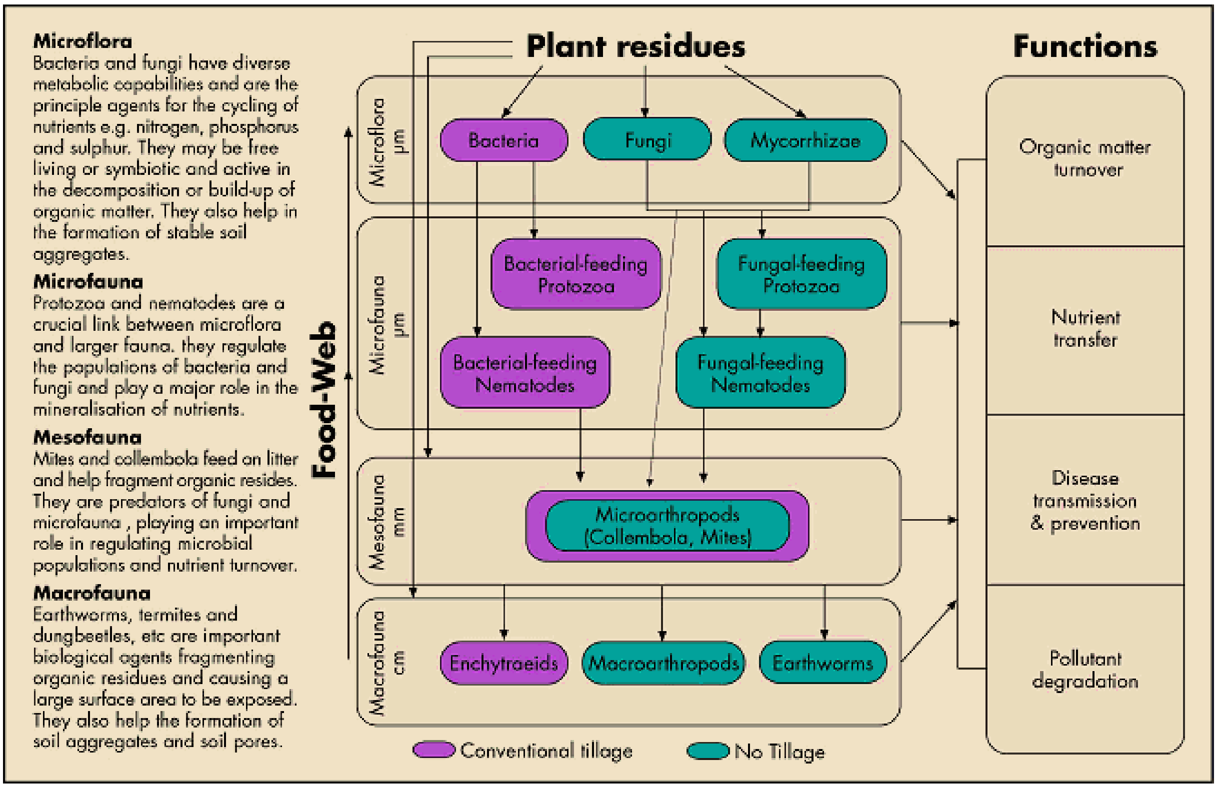

Figure 2: The key functions of soil biota (Soil Water Solutions, n.d.).

Quality of SOM is also very important, not just the quantity. Sarah Singla (pers. comm., July 2018) from Canet-de-Salars in France describes this relationship "*like having money in the bank but no credit card*".

Soil microorganisms need a diet with a C:N ratio near 24:1 (See Table 1). Bacteria-fungi relationships are also important. A healthy balanced soil should have bacteria:fungi ratio of 1:1. Bacteria dominated soils are common after many years of synthetic fertiliser and pesticide use. Bacteria are only 20-30% efficient at keeping carbon in the soil. Fungi are 40-50% efficient at keeping carbon in the soil (Hoorman & Islam, 2010).

An understanding of these ratios is important for grain producers to structure cropping rotations to enable enough residues to be left after harvest to:

1. Feed the soil biota;
2. Maintain sufficient ground cover; and
3. Add carbon.

Material	C:N Ratio
rye straw	82:1
wheat straw	80:1
oat straw	70:1
corn stover	57:1
rye cover crop (anthesis)	37:1
pea straw	29:1
rye cover crop (vegetative)	26:1
mature alfalfa hay	25:1
Ideal Microbial Diet	**24:1**
rotted barnyard manure	20:1
legume hay	17:1
beef manure	17:1
young alfalfa hay	13:1
hairy vetch cover crop	11:1
soil microbes (average)	8:1

Table 1: Carbon:Nitrogen ratios (The Daily Garden, 2017).

Chapter 3: Soil Biota

The soil is a living system. There are more living organisms in a handful of soil than there are people on Earth. Figure 2 shows the key functions of soil biota. Soil bacteria and fungi drive all soil processes globally. They are some of the smallest organisms in the soil. They are the principle agents for the cycling of nutrients and help in the formation of stable soil aggregates (Gupta, Neale & Leonard, 1997). They also serve as food for other organisms such as Protozoa and Nematodes. These protozoa and nematodes mineralise nutrients including nitrogen as ammonium for plants to use. Like humans they need air, water and food to survive. They die in high temperatures and in compacted soil. Just a 1% increase in the concentration of oxygen in the soil will significantly increase the activity of soil microbes (Stika, 2016).

The SFW is primarily made up of bacteria, fungi, protozoa, nematodes, arthropods and earthworms. These 'underground livestock' are the key to healthy soil, yet they are reliant on us to prosper. Roots and microbes need air, so poorly structured, compacted soils limit microbial prosperity. Fungicides kill rhizobia and microbes which are needed to produce and release nitrogen through bacterial processes from unavailable to available sources (Gupta, V., Neate, S. & Leonard E., 1997). Trials done by UK farmer David Miller (pers. comm., 2018) in 2017 demonstrated that di-ammonium phosphate (DAP) fertiliser applied with the seed at planting, significantly lowered mycorrhizal populations.

Soil microbes feed on, and digest straw and other crop residues. Other carbon inputs such as manure are also broken down by bacteria into a stable, plant available form. Fungi build and sequester carbon. They connect with plant roots and bring water and nutrients to them in exchange for sugars. Plant roots alone explore only 1% of the soil. Plant roots associated with fungi explore 20% of the soil (Hoorman & Islam, 2010). They are the key to building, capturing and keeping SOC.

Young plants exude large amounts of sugars, which bacteria feed on. Later in the crop cycle, the roots exude amino acids which fungi feed on. A greater population of bacteria and fungi fuelled by living plants help break down and degrade introduced chemicals in the form of pesticide and herbicide residuals (Joel Williams, pers. comm. 2018). This is a critical step in moving towards a regenerative agricultural system.

If the soil is in equilibrium, plants can fight off disease and insect pressures, reducing the need for crop protectant chemicals. Figure 3 shows how nutrients in the soil can influence the availability and uptake of each other. Foliar application of nutrients provides immediate elemental nutrition to plants but is also an indirect microbial stimulation. A small amount of foliar nutrition stimulates microbes to absorb more mineral nutrients from the soil. This opens a pathway for soil extraction, giving plants the energy to explore and extract more nutrients and water from the soil. Minerals in the right amount can reduce the need for crop protectant chemicals. Silicon, for example can increase the cell wall strength in plants, helping to protect them from disease (Dan Kittredge, pers. comm, 2018).

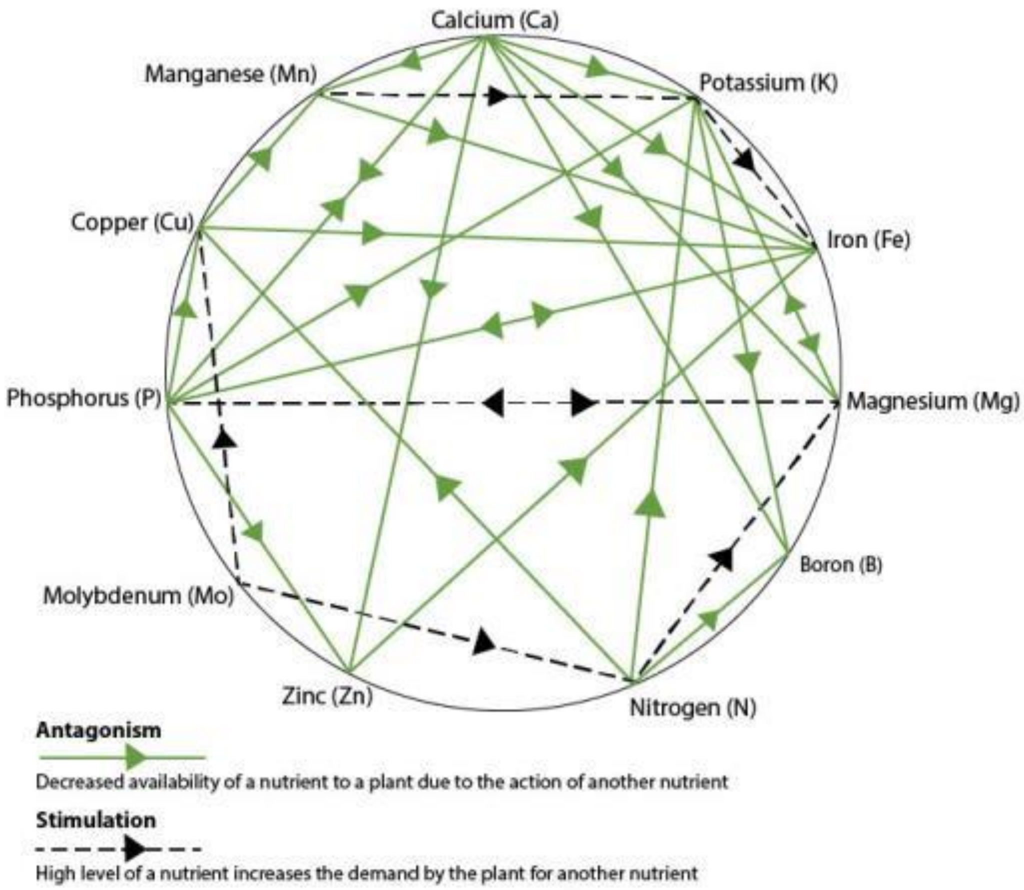

Figure 3: Mulders Chart (NutriAg, 2018).

Chapter 4: Soil Cover

Maintaining soil cover is one of the most important ways of improving soil health. Residue regulates soil temperature. At 54°C, 100% of moisture is lost to evaporation. At 21°C, 100% of moisture is used for plant growth (McEntire, 2011).

Uncovered soils can reach temperatures above 60°C during the summer months. At temperatures above 35°C some soil biology die, and above 60°C most beneficial microbes die. In contrast covered soils can be as much as 20 degrees cooler. Residue on the surface does not expose the soil to direct sunlight and the mulch also reduces evaporation (Ademir Calegari, pers. comm., 2018). Ideally, a living crop with full canopy will keep the soil temperature at its lowest over an Australian summer.

> *"At a soil depth of 2.5cm, there can be 11°C difference in soil temperature between soils with a living cover crop compared to bare soil"* (Rick Bieber, pers. comm., 2018).

Debate surrounds whether residues are better on the surface in contact with the soil or left standing. In Brazil, in high rainfall regions, residue on the surface is regarded as the best option. This lowers evaporation, can create an allelopathic effect for suppressing weeds, improves water infiltration and reduces erosion (Ademir Calegari, pers. Comm., 2018). The residues break down rapidly when in contact with the soil which is important considering there is only three months between consecutive crops in this region.

In some places where heavy rainfall is rare and smaller amounts of rainfall are more prevalent, standing residue can be better to capture rainfall. If wind is common, standing residue can create a microclimate for young plants to be protected and reduce wind velocity at the soil surface also reducing evaporation. Standing residue can also keep plants shaded in early crop development which may be of benefit in low rainfall environments like much of South Australia. In addition, plants will grow quickly to compete for sunlight in standing residue and there may be more nitrogen available initially (David Guy, pers. comm., 2018).

Cereal crops can generally be harvested by either a conventional sickle bar header, or a 'stripper header'. A 'stripper header' has fast rotating fingers to remove grain from the stalks, leaving the straw residue standing. Brice Custer from Hays, Kansas (pers. comm., 2018), believes he can capture and utilise 25mm more rainfall annually with the use of a stripper head over a conventional head.

Rick Bieber from Trail City, South Dakota (pers. comm., 2018), notes that tall thatched stripper straw reduces evaporation and is important for capturing CO_2. He believes it is important to look at nature.

> "*Nature does not mulch, cut, remove or incorporate with tillage, the residue from plants. It is important for the first breath of air young cotyledons take to be rich in* CO_2*. This improves the nutrition and resilience of the plant for its entire life*".

In order to maintain adequate soil cover in continuous cropping systems, plants with high carbon residues must dominate a rotation. Legume crops do not build 'soil armour' and should only be planted every 3-4 years if sown as a monocrop (Rick Bieber, pers. comm., 2018).

Decreasing row spacing to increase seed bed utilisation will also improve the time which the crop takes to cover the soil, resulting in greater yield, increased crop competition and less weeds (GRDC, 2011). A weed by definition is; 'any plant growing where it is not wanted' (Britannica, 2019). Weeds grow in bare soil, in excess nitrogen and where there is no competition. Nature will always try to cover and protect the soil. There are some alternatives to herbicides for weed control, they include:

- Plant competition (high plant populations);
- Diverse architecture (reduce sunlight);
- Allelopathy (some plants exude natural fumigants) (Figure 4 and 5);
- Livestock; and
- Diverse rotations.

Figure 4: Corn sown into rolled cereal rye cover crop (Jim Harbach farm, Loganton Pennsylvania, 2018). This amount of residue can create an allelopathic affect, as well as a physical barrier making it difficult for weeds to emerge.

Figure 5: The author standing in a mustard cover crop, planted as a soil fumigant. Groundswell, North Hertfordshire, UK, 2018.

Chapter 5: Cover Crops

A cover crop is a crop of single or multiple species planted to improve the soil, generally not for grain harvest, but can be grazed. The role of a cover crop is to cover the soil, reduce erosion, capture moisture, feed the biology, suppress weeds, and cycle nutrients (Stika, 2016).

Cover crops are grown all around the world for a variety of reasons:

- to stop wind and water erosion
- to improve the infiltration rate of rainfall
- to improve nutrient availability
- to reduce evaporation and soil temperature
- to keep soil biology alive and fed
- to build fungi and SOC
- to supress weeds
- to use excess water
- to provide feed for livestock

Cover crops will use water and nutrients, and there is also a cost for the seed and the seeding operation. Jay Fuhrer (pers. comm., 2018) sees these costs as an investment in improving the soil food web and building carbon in the soil is what the farmer gets in return. Over time, the economics of a healthy, resilient soil will outweigh conventional fallow systems. A fallow is only 25% efficient at storing water, and without cover, wind erosion can remove nutrients from fields before it is even visible. Fuhrer also notes that:

> "*Transpiration buys you carbon, evaporation leaves you salt*".

Green plants take energy from the sun and feed the soil organisms, who in turn build the soil and feed the plants. The most potent tool with which to build healthy soil is a live plant (Stika, 2016).

Cereal rye is one of the most common cover crops grown around the world. It produces a huge amount of biomass above and below the ground, it is excellent at fixing carbon and absorbing unused soil nitrogen. It is possibly the best cover crop for weed suppression, even providing an allelopathic environment after termination. Taller and faster growing than wheat, rye can serve as a windbreak and can trap snow or hold rainfall over winter, making it a popular cover crop in the northern hemisphere (SARE, 2012).

Obviously, more benefits are achieved with higher biomass. Evaporation and weeds are reduced if there is complete ground cover. However, all living roots and soil microbes hold water. In low rainfall environments such as South Australian summers, low water use plants need to be selected as covers. These hardy species include millets, sorghum, buckwheat, clovers and linseed. Perennial crops such as lucerne and clover can also be used to reduce the need to establish a cover crop in dry conditions after harvest. Annual cover crops such as grain sorghum and millet can be sown with winter cash crops but will only establish when soil temperatures increase. More research is needed to establish what species are best suited to South Australian soils and climatic conditions.

In some years there may be moisture available in the soil, post-harvest to germinate a timely sown cover crop, however this moisture will evaporate quickly after the grain canopy is removed. Cover crops will use water early but can recharge water later if terminated before grain fill. Plants expend energy to build roots (Dan Kittredge, pers. comm., 2018). Old roots provide compaction free areas for new roots to follow. This energy saving results in improved WUE and a healthier plant. The type of plants grown in a cover crop depends on many factors including moisture availability, temperature, humidity, seasonal length, rotation, residual herbicide carryover and purpose.

Cover crops, like cash crops produce green leaves, which produce sugars. These sugars feed microbes in the soil, which then unlock nutrients from organic matter to feed the plants. These living plants are building carbon. If there are no living plants (fallow) these microbes will eat crop residues and then organic carbon reserves to stay alive. To build SOC, fallow periods need to be removed from cropping rotations.

Cover crops can help manage nitrogen and crop residue cover on the soil. High carbon plants such as summer grasses will provide good soil cover and provide high carbon residue following a low residue legume crop.

Jim Harbach farms in Pennsylvania, USA (1,100mm annual rainfall), where he has increased his SOC from 2% to 5% over 40 years through no-till and dairy manure application and is now planting diverse cover crop mixes between his corn rows (pers. comm., 2018) (Figure 6).

Figure 6: Jim Harbach standing in a corn crop, intersown with a multi species cover crop in Pennsylvania, USA, 2018.

Chapter 6: Companions

> *"A soil inhabited by a single species of plant will not feed the soil organisms a proper diet"* (Stika, 2016).

Nature is full of diversity; monocultures are not natural. There will always be some weeds and different plants growing together in nature. Modern agriculture is predominately made up of monoculture crops (a single crop species). While this is efficient and simple, it has however, caused resistance to chemicals and natural selection of weed, insect and disease problems.

Companion Cropping

A companion is; '*each of a pair of things intended to complement or match each other*'. Companion cropping is the cultivation of plants that grow harmoniously together (Maximum Yield, 2019). This may be for any number of different reasons; including pest control, pollination, providing habitat for beneficial insects, maximising use of space, and to otherwise increase crop productivity. Companion cropping can offer improved weed control, better nutrient efficiency, disease suppression and improved WUE.

The roots of like (monoculture) plants, for example wheat, do not touch each other. They cannot share water or nutrients between each other. Companion plants, for example wheat/peas, do have the ability to touch roots and exchange nutrients such as nitrogen and phosphorus. This can be very beneficial to both companion plants (Rick Bieber, pers. comm., 2018).

There is a symbiosis between different plant species when grown together. This is not simply an exchange in nutrients, but mutual benefits including improved disease resistance, insect predation and WUE (Joel Williams, pers. Comm., 2018).

Research by Elsevier (2017) in France has shown evidence that legume and cereal companion crops are very synergistic:

> "*The companion plants had no significant effect on cash crop yield, but significantly decreased weed biomass by 56% relatively to a non-weeded control treatment, and 42% relative to a weeded control treatment. Therefore, the use of legume companion plants generally seems to enhance weed control without reducing crop yield*".

The legume plant does not supply much nitrogen to the cereal plant throughout its life cycle (it is available the following year), however there is a significant yield benefit to the cereal from this companion planting, as was shown by David Guy (pers. comm., 2018) in trials in France as shown in Table 2.

Crop	Nitrogen Applied	Yield
Wheat	0kg/ha	4.7t/ha
Wheat	135kg/ha	6.3t/ha
Wheat + Peas	0kg/ha	6.4t/ha

Table 2: Trial data of companion crop by David Guy

Companions should be selected for a reason, to complement one another. Lucerne (See Figure 7), clover, peas, flax, beans and radishes are all good companions with wheat. This system could possibly be implemented in dryland South Australian cropping areas. Guillaume Milard (pers. comm., 2018) has seen on his farm that wheat planted with daikon radish improves competition and roots deeper.

Figure 7: Sarah Singla standing in a wheat crop, under sown with perennial lucerne on her farm in Canet-de-Salars, France 2018.

Another example of companion planting includes millet, which recycles nutrients from deep in the soil to the surface very efficiently; planted with either corn, which exudes high pH (alkaline) root exudates; or beans, which exude low pH (acidic) root exudates, making them excellent companions for millet. Soybeans planted as companions can signal corn plants to close their stomata earlier when it gets hot, improving the WUE of corn (Harrington, 2018).

Buckwheat is a great phosphorus (P) scavenger, releasing 20-30kg/ha P from the soil. It is a fast maturing plant that provides a break from all disease pathogens in winter cereals and legumes. It can be harvested early when sown with a long season companion.

Linseed (flax) is a great companion with lentils and chickpeas (See Figure 8). There is less disease pressure in comparison with a monocrop. Harvest ability can also be improved. Linseed is also one of the best mycorrhizal host plants available.

Finally, beans sown with canola, wheat or oats show considerably less chocolate spot disease than monocrop beans (Harrington, 2018).

Figure 8: A companion crop of chickpeas and linseed at Jeremy Wilson's farm (500mm annual rainfall) North Dakota, USA.

Relay Cropping

Relay cropping (See Figures 9 and 10) is a combination of two cash crops growing together for a period, sown and harvested separately at different times. Modifications are necessary to the harvesting front to push the later maturing crop down away from the cutter bar, enabling the harvest of the earlier cereal crop. Relay cropping can offer a good option to add diversity in a crop rotation in some higher rainfall areas. The yield of the individual crops is generally about 70% of a monocrop, however combining both crops can result in a better gross margin per hectare. There is also less fertiliser and chemical expense due to higher crop competition and diversity (Steinlage; Koostra, pers. comm., 2018). The use of relay crops in South Australia may be limited due to insufficient rainfall and climatic conditions.

Figure 9: Relay barley and soybeans on Loran Steinlage's farm Iowa, USA.

Figure 10: Relay crop of wheat and soybeans on Rick Koostra's farm, Bluewater, Ontario, Canada.

Chapter 7: Diversity

> *"A diversified crop sequence prevents selection and build-up of the best-adapted pest populations*" (Barzman, *et al*., 2015).

Current crop production systems are highly productive. The use of fertilisers, chemicals and technology has enabled increasing yields, highly efficient operations and promoted simple crop rotations. However, this over-reliance on chemical control has resulted in weed and pest resistance, as well as declining nutritional value of the food we produce. There is therefore a need to design cropping systems less dependent on synthetic inputs.

Diversity improves the resilience of cropping systems. It can improve the plant's ability to fight insect and disease infestation and increase the WHC of the soil.

> *"Having diversity in your system is like having insurance*" (Gail Fuller, pers. comm., 2018).

The more above-ground diversity; the more below-ground diversity. Different plant species can be used to optimise nutrient scavenging and cycling from the soil. Higher plant diversity increases the amount of fungi, balancing the bacteria:fungi ratio, resulting in a more balanced, healthy, resilient soil (Mike Harrington, pers. comm., 2018).

Growing a diverse mix of plants feeds biology nutrients as they need them, unlike the annual addition of synthetic inputs. The more diversity; the faster soils will improve and become more regenerative. High carbon plants, growing as frequently as possible will keep biology fed and increase SOC at a rate much faster than simply retaining monoculture residues.

Monocultures and cereal/legume rotations are a barrier to improving our WHC, rooting depth and fungi populations. Monoculture legumes are devastating to soil health. They have a low C:N ratio, meaning they do not supply enough carbon to build or maintain SOC.

All cover crops should include a diverse mix of each of the following (Rick Bieber, pers. comm., August 2018):

- Warm season broadleaf
- Cool season broadleaf
- Warm season grass
- Cool season grass

An example set of cover crops can be seen in Figure 11 below.

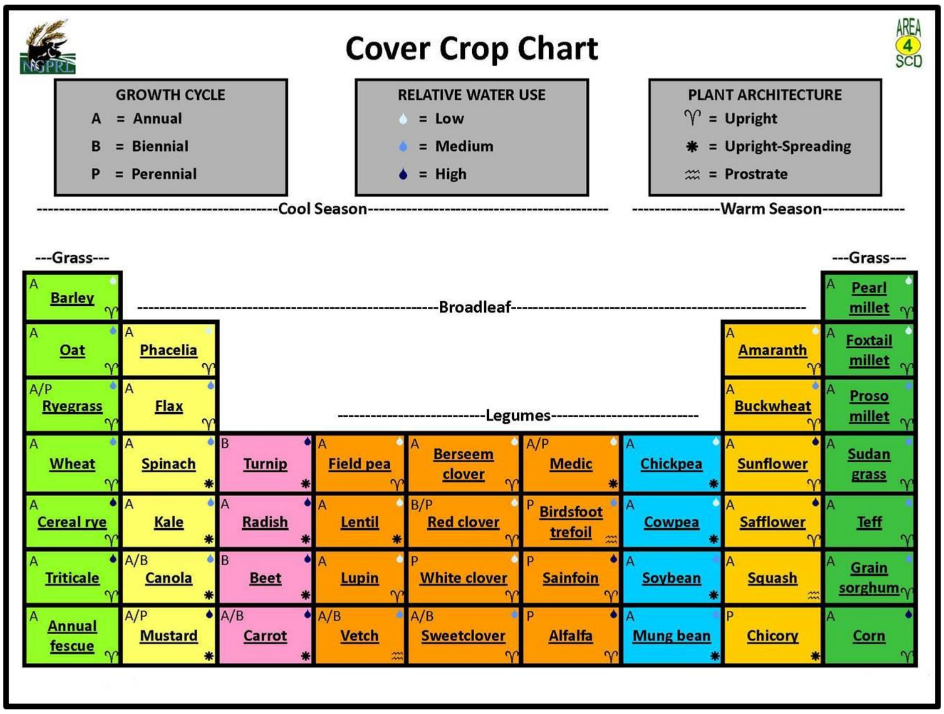

Figure 11: Cover crop chart (USDA, 2018).

Figure 12: Rick Bieber, a soil health practitioner and pioneer in RA, in a crop of sunflowers, which have been grown with zero applied fertiliser; Trial City, South Dakota, USA, 2018.

Chapter 8: Manure and Compost

The addition of manure and compost improves the quality and health of soils by:

- Increasing SOC
- Increasing WUE
- Increasing nutrient cycling and nutrient retention
- Increasing aggregate stability
- Increasing water infiltration
- Increasing water holding capacity
- Increasing resistance to compaction
- Decreasing bulk density (Schott, pers. comm. 2018).

Sarah Singla (pers. comm., 2018), states:

> '*Compost is like cake, manure is like chocolate, it provides the nutrients which feed crops*.

Application of compost improves the WHC and structure of the soil as well as supplying a stable nutrient supply. Compost is a better soil amendment than manure and emits significantly less odour, however manure supplies more mineral nutrition per tonne applied. The author believes that there is a better initial yield response from raw manure than from compost, due to its high nitrogen content (Pontifex Farming trial data 2007-2018). Applying compost or manure to the soil, especially if followed by tillage, does not restore soil health unless a favourable habitat for the soil food web is also maintained. Liquid manure contains a higher proportion of nitrogen in the ammonium form than solid manure, making it less stable when surface applied (Linda Schott, pers. Comm., 2018). From the author's own experience, in South Australia liquid manure is not commonly available for large scale application, with the primary source of manure being available from broiler poultry farms. Some of this manure is composted commercially, while other compost is produced from municipal waste, cattle feedlots and mushroom farms.

Manure can be mixed with woodchips, wood shavings, straw or municipal waste to improve the texture, structure and C:N ratio. A ratio of 30:1 is ideal for composting (poultry manure is approximately 6:1). Compost is produced from a feedstock, water and oxygen. The temperature needs to be maintained between 55 and 65°C, and the moisture content around

40-50%. This is achieved through regular water and oxygen addition for a period of three weeks. The composting process removes CO_2 and some nitrogen, causing a reduction in volume of approximately 50%. Stable compost has a temperature of around 43°C. It is then best to let cure over a period of about two months (Pleasant & Martin, 2008).

Static composting is a process that does not involve regular turning. The heat generated by the biology within the pile may need to be released through tubes. Static composting takes about 11-12 months to cure. Surface applied compost takes 18-24 months to become available to plant roots (Simon Parfay, pers. comm., 2018).

Manure can supply all the nutrients required for crop production. In the transition to a regenerative system, additional nitrogen and sulphur at a ratio of 10:1 may be necessary as yield potential increases, if soil biota are not adequately mineralising nutrients. In a system of annual application of manure, after four years; 47% of applied organic N is plant available annually. Approximately 20% of applied carbon is retained in the soil.

Manure supplies plant available nitrogen in three forms;

1. Nitrate N: 100% available in year of application;
2. Ammonium N: 75% available in year of application;
3. Organic N: 30% available in year 1, 10% in year 2, 5% in year 3, and 2% in year 4.

Ammonium N is immediately available to a growing crop like nitrogen from mineral fertilisers but it is subject to volatilisation loss to the air. This gas; ammonia (NH_4) is responsible for the odour of manure and is easily lost in the composting and spreading of manure. Retention of this form of nitrogen is important for the nutrient value to crops, but also for the social responsibility to the environment and neighbouring farms, towns and residential populations.

Retention rates of ammonium N vary based on application methods, incorporation time, manure source and climatic conditions (temperature, humidity, wind, rainfall). Warm temperatures increase the rate of ammonium loss to the air, and these losses are highest on warm, sunny days when soils are dry; whereas losses are lowest when conditions are overcast and cold, when soils are moist or during rainy periods (See Table 3). The estimated retention of manure directly injected into the soil will retain 100% of the ammonium N available (Christine Brown, pers. comm., 2018).

Storage of manure is also important and can greatly affect the quality and nutrient value of the manure. Covering manure piles with straw has shown to reduce NH_4 loss by up to 85% (See Figure 13) (Christine Brown, pers. comm., 2018).

Method	Time	Retention (%)	Temperature (^oC)
Incorporated	1 day	75%	<20 ^oC
Incorporated	3 days	65%	<20 ^oC
Incorporated	5 days	55%	<20 ^oC
Spread on bare soil		34%	<20 ^oC
Spread on bare soil		20%	>25 ^oC
Spread on crop residue		50%	<20 ^oC
Spread on crop residue		35%	>25 ^oC
Spread on living crop		66%	<20 ^oC

Table 3: Estimated proportion of ammonium N from manure retained in year of application (Brown, 2016)

Figure 13: Manure windrow in France covered with straw to reduce ammonia loss.

Compost Teas

Compost teas are used to fertilise crops all over the world. Trial results vary significantly and are hard to replicate. The brewing process is critical to quality. If not brewed correctly, results can be unreliable and even detrimental if high in bacteria. There are people such as Derek and Tannis Axten in southern Saskatchewan, Canada, who are successfully brewing and using compost teas and achieving great results. However, many have yet to replicate results or quantify any benefits with their use. Teas need to be sprayed on crops in cool weather, in good growing conditions for best results.

Pelletised Manure

Pelletised manure is an efficient product to freight, handle and use. It is much more expensive due to the manufacturing process involved. Application rates can be lowered substantially as the product can be placed in the soil, next to the seed at planting time through an air-seeder or drill. In France, David Guy (pers. comm., 2018) is an organic farmer using solely manure for his crop nutrition. He spreads 4t/ha of chicken manure into his cover crop, then uses 250kg/ha of chicken manure pellets (5% N) drilled at seeding with his cash crop seed.

Chapter 9: Measuring Soil Health

Soil health is an integrated understanding of physical, chemical and biological components of the soil. The five principles of soil health are:

- Armour the soil
- Minimise soil disturbance
- Increase plant diversity
- Living roots in the soil all year
- Integrate livestock grazing (Stika, 2016).

Digging in a field with a shovel will instantly give some indication of the soil's inherent properties and an insight into that soil's health. Structure, aggregation, smell, colour and presence of organic matter and earthworms are all easily distinguishable characteristics. WUE and nutrient analysis are also great indicators of soil health.

There are several matrices for measuring soil health, they include;

- Infiltration rate of water into soil
- Organic carbon
- Biological respiration rate of soil

Nematodes and earthworms are also both good indicators of soil health. Earthworm numbers in a trial in France conducted by Guillaume Milard (pers. comm., 2018), taken during spring in six replicated plots, showed an incredible difference from tillage practices:

No-till – Average 196 earthworms.

Tillage – Average 60 earthworms.

A soil test can give a good indication of nutrient quantities and balances within the soil. If a soil test to measure SOC is taken in spring when plants are pumping carbon into the soil through photosynthesis, it may vary considerably from a test taken during a fallow period in summer. The roots of growing plants will swell up with water, displacing more volume in the soil sample. Similarly, microbial tests will vary immensely depending on the time of year, moisture available and crop type/species planted.

"*Soil test SOC will differ by up to 3% depending on the time of year sample is taken*" (Rick Bieber, pers. comm., 2018).

The Solvita test measures the amount of carbon dioxide (CO_2) respiration of the soil. Bacteria and fungi emit CO_2 as they feed (Joel Williams, pers. comm., 2018). This is a good measure of how much life is in the soil. The ratio of bacteria:fungi is very important. There needs to be equilibrium in the system, ideally a ratio of 1:1 is ideal for grain cereal crops.

Infiltration rates after saturation are a good test for extraction of water from soil as well as infiltration. If soils infiltrate water readily, plants can extract water easily. This results in less energy required and better WUE. Horizontal plates in a soil are a sign of compaction and will slow infiltration rates. Jay Fuhrer (pers. comm., 2018), from Bismark, North Dakota, noted that:

> *"A healthy soil should infiltrate 50mm of rainfall within 10 minutes*."

Figure 14 shows the water infiltration of a simulated rainfall event on the same soil with different management practices.

Figure 14: Rainfall simulator water infiltration demo; tilled soil (left) vs no-till with cover (right), Kansas, USA, 2018.

Conclusion

Despite practicing no-till, retaining all crop residues for the soil and applying chicken manure on an annual basis, it has not been possible to build SOC much beyond 2.5% using current systems of annual winter cropping on Yorke Peninsula.

How to significantly increase soil organic carbon?

Growing more carbon is the key to significantly increasing SOC. This means growing high carbon plants more often and fewer legumes which have a low C:N ratio. More roots, more often through diverse cover crop species or companion crops in combination with annual cash crops will fix more carbon from the atmosphere into our soils and produce more carbon residue to feed the biology.

What role does biology have in soil health?

Biological activity controls over 90% of all soil functions. Soil biology in equilibrium can increase nutrient cycling, WHC and soil aggregation. These are all good indicators of a healthy and regenerative soil. Soil biology should be considered in all agricultural production decisions.

Are cover crops a viable option in low rainfall areas of South Australia?

Cover crops can be a viable option in South Australia. The opportunity to plant cover crops may not be available every summer, however winter cover crops and companion plantings are viable options and need further investigation. These regenerative systems including cover crops in combination with other soil health practices can be adopted in this state with success. The right cover crop species and combinations which tolerate dry, low humidity climates will need further investigation.

Only heavy cover crop residues will provide an allelopathic environment to reduce the emergence of weeds. There are many different cover crop species available. The selection or combination will vary depending on what reason the cover crop is being grown. Some plants are more drought tolerant, produce more carbon, cycle more nutrients or can help alleviate compaction better than others. If planting in a cash crop rotation, cover crops need to be terminated prior to grain fill to limit water use. This is especially important in low rainfall regions.

Is it possible to keep soil biology alive over a hot, dry summer?

Maintaining soil cover reduces evaporation, soil temperature and provides food for microbes. This is essential to keep soil biology alive and to store enough water to grow more plants. No-tillage with as little soil disturbance as possible is the cornerstone to improving water infiltration, maintaining adequate cover on the soils surface, keeping soil temperatures down, keeping biology alive and improving soil structure. Tillage and excess nitrogen promote weeds. We need to match plant requirements with nutritional inputs in balance. Weeds do not contribute anything beneficial to the soil. They are nature's way of protecting the soil when there is no other cover.

How to use and apply manure more efficiently in a no-till cropping system?

The maximum retention of nitrogen without tillage when applying manure is optimised by spreading into a living cover or cash crop in cool weather. Raw manure provides more nutrition to plants, but composted manure and other carbon sources can improve soil structure and aggregation. The addition of manure or compost in isolation at common application rates of 2.5t/ha – 5t/ha annually will not substantially increase SOC.

Recommendations

Recommendations are designed around soil type, rainfall, rotation, elevation and climate for grain production in South Australia. However, the principles of improving soil health are the same. Practices may vary, cover crop species and combinations will vary, and seasonal conditions will possibly be the most determinate factor.

- **Build more carbon.** There is potential to build SOC in grain systems by planting cover crops after winter cash crops. This combination is dependent on moisture availability after harvest. Perennial species under-sown with cash crops could maintain living roots after cash crop removal. A cover crop could be planted over winter, terminated in spring and higher value summer crop planted for harvest following winter cover termination. Grow higher carbon plants more often to feed the soil food web. Legume crops do not build carbon.
- **Apply manure and compost.** Synthetic fertiliser is detrimental to soil fauna. Manure and compost are healthy additions to soil, providing nutrition to plants, food for microbes and structure to soils. Spreading manure in cool weather, into living plants is the most efficient way of capturing NH_4 in a no-till system.
- **Increase diversity.** This is the limiting factor in annual cropping areas of South Australia. The author believes that diversity of plant species is the missing link to improving soil ability to mineralise more nutrients, store more water, combat disease and weed pressure and ultimately improve soil health. Integrating diverse species into cropping systems, when opportunities arise, is essential to improving soil health. Companion cropping should also be trialled and evaluated.
- **Maintain cover.** Soil temperature is dependent on cover. Soil biology cannot survive without adequate soil cover over summer. Living plants are optimal, however at times of no rainfall this is difficult. Reduced grazing, growing higher carbon plants and maintaining C:N ratios are important to maintaining adequate cover. A stripper head for harvest and utilising a low disturbance disc for seeding will maintain residue cover for extended periods.
- **Alleviate compaction.** Soil biology needs to respire. Structured soils improve water infiltration and extraction. Less energy is required for plants to grow roots if soil is low

density. In some soil types compacted soils can be quickly alleviated mechanically by means of a deep ripper, or ultimately with the use manure application and plant roots.

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Plain English Compendium Summary

Project Title:	Improving soil health with manure and cover crops
Nuffield Australia Project No.:	1808
Scholar:	Grant Pontifex
Organisation:	Pontifex Farming 481 Pontifex Road Paskeville, SA 5552
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Objectives	This report sets out to investigate the ability to improve soil health and profitability in dryland grain producing regions of South Australia, by answering the following questions: • How to significantly increase soil organic carbon? • What role does biology have in soil health? • Are cover crops a viable option in low rainfall areas of South Australia? • Is it possible to keep soil biology alive over a hot, dry summer? • How to use and apply manure more efficiently in a no-till cropping system?
Background	Current systems of grain production rely on high input and high cost of synthetic chemical and fertiliser solutions. Agriculture is being increasingly scrutinised by environmental, political and other consumer groups. Declining terms of trade continue to weigh on the profitability of farmers. Healthy soil will produce healthy food and improve our profitability.
Research	Research has been conducted in Australia, New Zealand, Brazil, Mexico, USA, Canada, Ireland, France and the Netherlands.
Outcomes	This report outlines the benefits of using regenerative agriculture practices, including the role of biology, the use of manure and cover crops to improve soil health.
Implications	Improvements in soil health results in better water use and nutrient efficiency, safe nutritious food production, reduced variable input costs and a sustainable grain production industry.
Publications	Nuffield Australia National Conference, Brisbane, Queensland. September 2019