Farming for the Future

Optimising soil health for a sustainable future in Australian broadacre cropping

A report for

By Alexander Nixon
2017 Nuffield Scholar

March 2019
Nuffield Australia Project No 1709

Supported by:

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Executive Summary

By definition, sustainable and successful farming businesses depend upon the health of their soils. For many years, conventional farming practices have been degrading soils, creating issues such as erosion, and negatively affecting crop yields. Full-disturbance tillage of the soil and whole paddocks left bare to fallow, goes against the laws of nature. A recent shift in farming practices towards minimum tillage has seen many benefits – yield increases, reduced erosion, improved cover retention and better water infiltration to name a few. The zero-till revolution has been paving the way for the agricultural industry to further improve management practices, in a push towards biomimicry.

The findings of this report indicate that farming in nature's image is increasingly important to maintaining soil health in agricultural operations. Bio-diversity and ground cover retention are both key elements to obtaining optimal soil health. Multi-species cover cropping is an emerging innovation in soil health management proving to be extremely effective at incorporating both of these elements.

This report reviews the functions of multi-species cover crops as ground cover for weed suppression, erosion prevention, increasing soil organic matter levels, and improving water infiltration and moisture retention. It also investigates the effects of bio-diversity on soil function, with an analysis of the significant interactions provided, including microbial activity, the bacteria to fungi ratio, the carbon to nitrogen ratio, and carbon and nutrient cycling. Key findings indicate that the species-richness effect on soil health is predominantly related to root biomass production, which stimulates growth and diversity in microbial communities within the soil, balances the bacteria to fungi ratio, and generally creates synergy between all soil elements and processes to promote a healthy soil ecosystem.

The logistics, considerations and financial viability of incorporating multi-species cover crops into broadacre cropping rotations is also assessed. Research shows that despite initial financial deficits being possible in early cover-cropping seasons, the long-term soil health benefits prove to be profitable through increased yields and decreased costs on fertiliser and chemical inputs.

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Foreword

I am many things… I am a passionate farmer and a somewhat cursory cattleman. I am a business owner, a husband, a son and a brother. But first and foremost, I am a father. In my life, I want nothing more than to do for my two boys, what my father did for me. I want to pass on the foundations of opportunity and the tools my children need to build themselves a happy and successful life of their own. I want to pass on to them strong morals, work ethic, resilience and common-sense. And I want to leave to them, what I consider to be some of the best dirt you can find – some of which has been in my family for over a century, farmed and grazed formerly by my father Archibald Nixon, and his father Alexander Nixon. What I don't want to do, is leave them with an abundance of tired, worn out, unproductive soil, de-void of nutritional value from years of over-farming and a lack of care.

My family and I own and run a 21,000-acre cattle and cropping operation on the Western Darling Downs in Queensland, Australia. Since taking over the management of our cropping sector in 2006 after the passing of my father, I have been gradually making the shift towards zero-till practices, better soil management and ultimately, improved soil health.

When I first started out on my Nuffield Scholarship, my intention was to research ways of improving soil carbon in dryland farming operations, but the information I found uncovered much more than that. What my studies have taught me, is that soil is far more complex than even the world's leading soil scientists can understand. Looking at improving just one element of soil is futile. Total soil health quickly became the focus of my research, through mimicking the fine balancing-act of nature.

Maintaining adequate levels of carbon, nitrogen, water, microbial activity, mycorrhizal fungi and bacteria, and the availability of many more essential nutrients and minerals, managing soil structure, keeping cover on the ground – all these things are integral to the longevity of the soil and its future productivity. There is no one magic input that can fix depleted soils. There is a whole host of activities and relationships performed when living plants are growing within soil, and it is these interactions which fix soil health. Working these findings into broadacre, dryland farming arrangements for the sake of future sustainability, is both necessary and ambitious, but definitely attainable.

Farming for the future has always been a passion of mine, and I hope my research instils into anyone who reads it, a drive to farm better and think bigger. To farm with the next generation of farmers in mind, not just the bank account balance. I want to pass on my findings to my business, and to the wider agricultural community. To put practices in place that will emulate my findings, and I want to pass those onto my boys so that they too know how to farm respectfully in years to come. I want to contribute to the industry, two new farmers, with open minds and full hearts. Kenrick Riley (1990) described my father as having a "*habit of always looking forward*". I believe this characteristic is crucial to our whole industry, and it is certainly one of my father's many admirable qualities that I truly hope my two boys inherit.

Figure 1: Alexander Nixon (Author) with sons, Archie (left) and Eddie (right) in their wheat crop at "Jay-Dee" on the Western Darling Downs, Queensland.
Source: A.W. Nixon (2017)

Acknowledgments

I would like to thank Nuffield Australia for affording me this amazing opportunity. It has been an incredible eye-opening experience, providing an opportunity to view the world and where Australia sits within global markets. Thank you also to the Grains Research Development Corporation (GRDC) for its generous investment in Nuffield and for funding my studies.

Throughout my travels I encountered many people who went above and beyond to accommodate me and my research. Particular mention must go to the Noble Research Institute in Ardmore, Oklahoma and everyone there who was involved in organising and coordinating meetings and a tour for me and my family.

In addition, I want to thank Nuffield Scholar Geraint Powell, who vacated his two-bedroom townhouse in England for my family and I to stay in, and for helping to arrange farm visits during our stay. Chontell and the team from I Travel Griffith were incredible during our travels, their attention to detail and their willingness to help was greatly appreciated.

I was also blessed with a great group of people on our Chile Global Focus Program (GFP), and would like to thank them all for bringing a depth of information and character to the experience. The GFP is something that I will never forget.

Most of all I would like to thank my beautiful wife Ali, and my two boys for supporting me through this. I had never even heard about Nuffield until my wife and long-term employee, Chester, nominated me for this scholarship behind my back and I am truly grateful for that. Although if I had known how much I was going to miss my wife I would never have left the bloody country!

Abbreviations

C	-	Carbon
C:N	-	Carbon : Nitrogen
GFP	-	Global Focus Program
GRDC	-	Grains Research and Development Corporation
LEAF	-	Linking Environment and Farming
MGT	-	Minimum Germination Temperature
N	-	Nitrogen
NSW DPI	-	New South Wales Department of Primary Industries
P	-	Phosphorous
SOM	-	Soil Organic Matter
USA	-	United States of America
USDA	-	United States Department of Agriculture
WIU	-	Western Illinois University

Objectives

The objectives of this project were to research organisations and farmers trying to improve soil health across the world, with particular reference to:

- Research facilities in the United States of America (USA) investigating soil health and the relevant contributing factors thereof.
- Farmer implementation of cover crops and regulated grazing to improve organic carbon levels, in both England and the USA.
- Establish how this information can be applied in a broadacre dryland cropping scenario, with specific consideration to the logistics and financial viability of incorporating cover crops into cash crop rotations in Australia.

Chapter 1: Introduction

Soil health is the linchpin of the entire agricultural sector. As Lloyd Noble once said, "*No civilization has outlived the usefulness of its soils. When the soil is destroyed, the nation is gone*" (Noble Research Institute, 2017).

Figure 2: Author, Alex Nixon with sons Eddie and Archie visiting the Noble Foundation, Ardmore, Oklahoma Source: A.W. Nixon (2017)

Traditional farming methods and monoculture crops have been evolving for thousands of years. The practice of farming is thought to have started about 12,000 years ago, with the domestication of livestock, and soon after, the cultivation of crops such as wheat, barley, peas and lentils (Lambert, 2017). By about 4,000BC, people in central Europe were using oxen to pull ploughs and wagons, and the heavy plough came about some time throughout the middle ages (Lambert, 2017). Around this same time, the concept of the three-field system first appeared, where that land was divided into three large fields, with two fields planted to crop while the third was left fallow (Lambert, 2017). This is a notion which remains commonly utilised today. From the time of the Industrial Revolution, and continuing throughout the 20th

Century, farming became increasingly mechanised. Horses were replaced with tractors and large-scale farming became more common place.

These conventional full-disturbance farming practices, together with the introduction of synthetic fertilisers and chemicals, and the continuation of single-species cropping, have gradually led to the degradation of soil structure and compromised soil health. Tillage can have deleterious effects on soil health, as it physically breaks down soil aggregate size and can also cause soil compaction (GRDC, 2017). The decrease in soil aggregate size leaves the soil more susceptible to wind and water erosion and reduces water infiltration levels, and tillage can also have detrimental effects on soil micro-organism populations (GRDC, 2017). Soils for Life (2017) claims that between one and 20 tonnes of topsoil is lost for every tonne of food produced from both the 1.5 billion hectares farmed globally and the 40 million hectares farmed in Australia. Current farming practices are also estimated to be losing five-to-ten tonnes of carbon per hectare per annum (Soils for Life, 2017). These issues are further exacerbated by leaving country bare through long fallow periods. Nielsen and Calderon (2011) state that:

> *"The various combinations of fallow frequency, tillage, and chemical weed control have effects on surface soil residue quantity, orientation, and duration, which subsequently affect surface soil organic matter content, soil physical structure, precipitation storage, nutrient availability, microorganisms, erosion potential, and ultimately, crop production."*

Clearly, the health and biology of the soil is paramount to a farming business, and progressively more farmers are beginning to address these issues. Over the past 100 years there have been many advances into agricultural science and technology, none however, more important than the practice of zero-till farming to minimise the impact on soil structure. Zero-till involves retaining stubble from crops as ground cover, and utilises new technologies such as minimal disturbance planters, controlled traffic and precision agriculture systems such as auto-steer. Engaging these practices on a farm can capitalise on improved paddock traffic and avoid the problems for crop growth caused by soil compaction (GRDC, 2017). In Australia, large-scale beginnings of no-till farming were first introduced in the Western Australia grainbelt in the 1990's and according to the GRDC, the six countries with the largest areas under no-till are the USA, Brazil, Argentina, Canada, Australia and Paraguay, with a total adoption area of over one million hectares (GRDC, 2017).

While retaining stubble as ground cover contributes significantly to improved soil health and structure and minimising erosion, abandoning physical disturbance of the soil is only one piece of the picture. Recently, studies in Texas and Oklahoma in the USA have been focused on the importance of bio-diversity and the subsequent correlation to microbial activity, with the experimentation of multi-species cover crops to rejuvenate soil health and biology. Figure 1 below exhibits the relationship between conserving ground cover on the soil surface, sustaining Bio-Diversity through a cross-section of plant species, and climatic conditions such as sunlight, temperature and rainfall. While elemental factors are unpredictable and cannot be controlled, ground cover and bio-diversity can be managed through modern farming practices – primarily multi-species cover-cropping in conjunction with zero-till – enabling agricultural businesses to capitalise on good seasons, improve soil function efficiency during periods of extreme weather, and sustain soil integrity for the long-term.

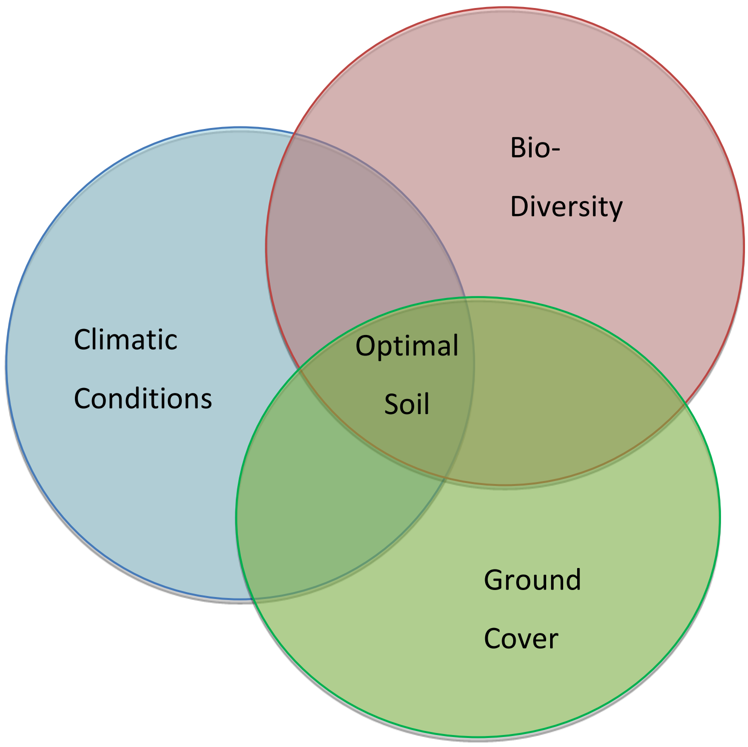

Figure 3: The symbiotic relationship between Climatic Conditions, Bio-Diversity and Ground Cover required to obtain optimal soil health levels. Source: A.W. Nixon (2017)

Regenerative agriculture is only in its infancy, however current global studies indicate that the future and sustainability of agriculture is increasingly reliant on biomimicry. In the words of Ray Archuleta (2017), "*If you are not farming in natures' image, you are an idiot*". This report collates the findings from the research of sustainable farm management practices conducted across numerous countries, including: Brazil, Chile, United States of America, Canada, England, Scotland, Italy and The Netherlands. The following chapters will explore the benefits of cover crops as ground cover, the relevance of bio-diversity in multi-species cover crops and soil function, and finally, the logistics and financial viability of incorporating multi-species cover crops into Australian broadacre dryland cropping arrangements.

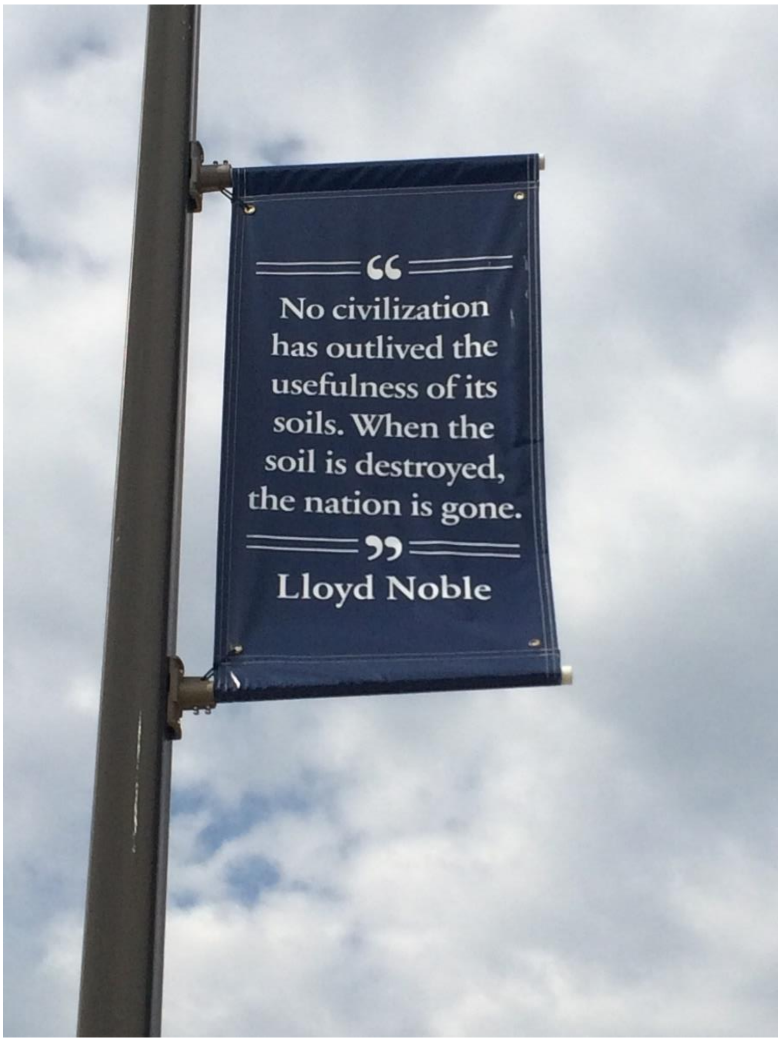

Figure 4: Numerous sustainable agriculture quotes displayed on flags were dotted around the Noble facility. Source: A.W. Nixon (2017)

Chapter 2: Cover Crops for Ground Cover

Maintaining cover on the ground is essential to soil health on a multitude of levels. As the name implies, cover crops aim to achieve exactly that. They are intended to be sown after the completion of a cash crop, in place of long-fallowing. Cover crops are typically left to grow until the milky stage of seed production, or until sufficient biomass has been obtained, after which point they are terminated – usually either lightly tilled in, mowed or rolled/crimped – with the residue remaining as ground cover. The New South Wales Department of Primary Industries (NSW DPI) (Lang and McDonald, 2005) explains that there are two main components to ground cover: canopy cover and contact cover. Canopy cover refers to herbage standing over five centimetres tall, while contact cover is any herbage which comes in physical contact with the soil, and can include prostrate stems, leaves, litter and the basal areas of plants (Lang and McDonald, 2005). Weed suppression, prevention of erosion, increased soil organic matter (SOM) levels and improved water infiltration/moisture retention, can all be achieved by implementing cover crops.

Case Study: JRH Grain Farms

The author met with Russell Hedrick of JRH Grain Farms during the 2017 Southern Soil Health Field Day in Hickory, North Carolina. JRH Grain Farms operate 800 acres, growing non-genetically modified varieties of corn and soybeans, white wheat, black oats, triticale, barley, and pasture-fed animals including cattle, sheep and pigs.

They initially began implementing three species of cover crops to aid in the reduction of erosion issues and winter weeds, however the following cash crop season, they noticed many subsequent benefits, such as nutrient cycling, reduced fertiliser and herbicide requirements, weed suppression, increased brix levels in plants and a reduced insecticide use. Some years later and having continued cover crop rotations increasing from three species up to 11 species and more, Hedrick asserted that some areas of the farm boasted SOM levels in excess of 5%.

With an average rainfall of 46 inches, Hedrick also explained that these increased SOM levels and the protective cover achieved on the soil surface from the cover crops assisted in higher water infiltration and moisture retention, allowing him to optimise water storage capacity within the soil and capitalise on the local high rainfall levels.

JRH Grain Farms have experienced success using sharp coulters and double disc openers for planting cover crops, and to assist the economics of incorporating multi-species covers, have introduced animals alongside their cash crops. Hedrick claims that this has extended the time that the ground is earning money, and also increases biology in the soil from mob grazing.

2.1 Weed Suppression

Thick, thatched cover as shown in Figure 5, provides the ability to restrict weed growth without the use of chemicals.

Figure 5: Thick, thatched residue from a cover crop helps retain moisture and suppress weeds in corn crop on a North Carolina property. Source: A.W. Nixon (2017)

Several elements contribute to weed suppression by cover crops, both when the crop is growing, and post crop termination, being:

- Direct competition.
- Allelopathy (the release of plant growth-inhibiting substances).
- Blocking of stimuli for weed seed germination.
- Altering soil microbial communities to the detriment of some weed species.
- Physically hindering weed seedling emergence.
- Promoting fungi pathogenic to weed seedlings.
- Tying up Nitrogen (N).

A trial conducted by K-State Research and Extension (2016) surveyed weed growth in three scenarios in a plot in Kansas, with comparisons between a bare strip, oat cover crop and a mixed cover crop. After approximately 2.5 months, the weed count in the bare strip was measured significantly higher than both cover crops, as per the tabulated results below.

Trial Plot	Weed Count (/m²)
Bare Strip	14.2
Oat Cover Crop	7.2
Mixed Cover Crop	1.2

Table 1: Trial Plot Data (K-State Research and Extension, 2016)

2.2 Prevention of Erosion

Fast-growing cover crops keep soil in place, prevent crusting and protect against wind and rain induced erosion. Above the surface, the crop residue and cover canopy acts as an armour against the direct impact of rain droplets and wind. NSW DPI (2005) explains that falling raindrops possess energy which dissipates upon striking bare soil, detaching and relocating soil particles and damaging soil structure. These detached particles form a surface seal which inhibits water infiltration and increases run-off. Long term cover crop use can alleviate water infiltration problems, consequently reducing run-off which otherwise causes the transportation of topsoil (Sustainable Agriculture Research and Education, 2012). This theory is further supported by the following graph which illustrates the average annual soil loss dependent on the level of ground cover maintained, from sites on the Eastern Darling Downs.

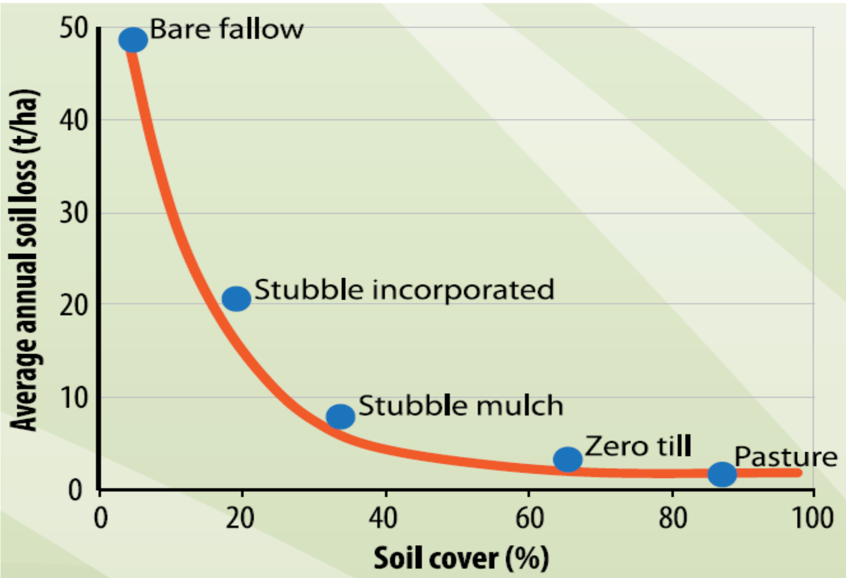

Figure 6: Soil loss observed depending on the level of surface cover on sites from the Eastern Darling Downs. Source: Soil Quality Organisation (2017)

2.3 Increasing Soil Organic Matter

Ground cover not only protects the surface and structure of the soil, but also increases arguably the most important component in soil: organic matter. SOM refers to any plant or animal material contained within the soil at varying stages of decomposition, cells and tissues of soil organisms, and the substances excreted by soil organisms. Despite making up only 2-10% of the soil mass (Hoyle, 2013), without organic matter, soil is dead; it becomes nothing more than finely ground rocks. Cultivation and cropping have led to a substantial decrease of SOM within the Australian cereal belt, with long-term SOM losses often exceeding 60% from the top 0-0.1m depth after 50 years of cereal cropping (Dalal and Chan, 2001).

While the depletion of SOM can occur incredibly rapidly through poor farming practices, conversely, replenishing some elements of SOM can take exceptionally longer. SOM is composed of four main fractions, they are:

- Dissolved Organic Matter.
- Particulate Organic Matter.
- Humus.
- Resistant Organic Matter.

Table 2 below describes each SOM fraction and the relative turnover time for residues to move through each "pool", along with relevant composition factors which influence the overall growth rate of total SOM.

Fraction	Turnover Time	Composition
Dissolved Organic Matter	Rapid – can be from minutes to days.	Predominantly soluble root exudates, simple sugars, decomposition by-products. Makes up less than one percent of total SOM.
Particulate Organic Matter	From months to decades.	Both fresh and decomposing plant and animal matter with an identifiable cell structure. Makes up 2-25% of total SOM.
Humus	Decadal (can range from tens of years to hundreds of years).	Comprises older, decayed organic compounds resistant to decomposition, including structural (eg. proteins/cellulose) and non-

		structural (eg. humin, fluvic acid) organic modules. Often makes up more than 50% of total SOM.
Resistant Organic Matter	Anywhere from hundreds to thousands of years.	Relatively inert material that consists primarily of chemically resistant materials or remnant organic materials such as charcoal. Usually makes up to 30% of total SOM.

Table 2: Organic Matter Fractions and their Turnover Time and Composition (adapted from Hoyle, 2013)

Undoubtedly, restoring and maintaining SOM must become a priority in sustainable agriculture. Integrating cover crops is one proven method of replenishing SOM, as evidenced by Gabe Brown during the 2017 Annual Southern Soil Health Field Day in North Carolina, USA. Replicated trial data from Brown's farm in North Dakota has shown impressive improvements in SOM levels following several consecutive years of cover cropping, where organic matter increased from a mere 1.2% to a solid 6.7% (Brown, 2017). The residue from cover crops slowly breaks down over time, providing food for soil microbes and replenishing the actively decomposing pool of SOM within the soil. Higher SOM levels are also closely linked to increased moisture retention.

2.4 Improving Water Infiltration/Moisture Retention

Water infiltration and water-holding capacity are equally influential on both soil health and crop production. This is particularly true in the Australian hot, dry climate, where water is frequently the leading limiting factor in crop production. Ground left bare tends to seal over, forming a hard crust which is impenetrable by rain. This causes precipitation to sheet-off instead of infiltrating the soil. According to the NSW DPI (2005), without adequate ground cover, up to 85% of the rain from an individual storm can be lost as run-off. Cover on the ground increases water infiltration by trapping surface water and by providing pathways for water to enter the ground through the crevices created by root systems. Contact cover impedes and slows water run-off, giving it more time to infiltrate and to allow the deposition of sediment (NSW DPI, 2005). This cover should preferably be living plants, since attached material is more effective than unattached material (litter) as the former is less likely to be transported in water run-off (NSW DPI, 2005).

Additionally, the increase in SOM through cover cropping further leads to greater water-holding capacity. SOM acts as a "sponge" in the soil, for the retention and release of water to plants, and can hold more than its own weight in water (Reicosky, 2013) Resource Conservationist KR Ethridge (2017) states that "*a one percent increase in soil organic matter content can hold an additional 19,000 gallons of water per acre*". That is equivalent to approximately 71,920 litres, which is a remarkably significant increase. Breaking it down even further, General Jefferies from Soils for Life (2017) says that for every one gram of carbon, soil can hold eight grams of water.

Chapter 3: Soil Function and Bio-Diversity through Multi-Species Cover Crops

The soil ecosystem is heterogeneous in nature, and the inter-relationships between all soil components are multifaceted. Plant bio-diversity has proven to be a key factor when considering soil health, as different plants serve a variety of purposes both above and below the soil surface. As Rick Haney says, "*plants fix soil*" (2017). Maintaining a diverse range of plant roots aids in preserving an array of different microbe communities and helps sustain the balance between fungi and bacteria, and also moderates the Carbon:Nitrogen (C:N) ratio. Concurrently, different plant breeds achieve varying degrees of cover on the soil surface and each species contributes divergently to both the carbon and nutrient cycles, dependant highly on the size and shape of the plant components, including leaves, stems and roots. These functions are all necessary for obtaining optimal soil health and are heavily inter-laced and tend to overlap.

Case Study: Allison Farms

In 1989, the Agriculture Department of Western Illinois University (WIU) discovered Allison Farm – a historically pesticide-free farm using limited fertilisers – on 80 acres of land located near Roseville, about 29 kilometres from the WIU campus in Macomb. The department wanted to secure this land, being a rare find in the area, so that it would be well-positioned to conduct research and trials for low input sustainable agriculture which was one of the USDA's new research initiatives at the time. Now called Allison Organic Research and Demonstration Farm, the WIU's Organic Agriculture Research Program rents the land annually from the Allison family, who remain the current owners. The program's immediate goals are to develop and test practical and economic impacts of alternative soil and crop management strategies.

Trials at the 2017 Allison Farm Field Day were looking at capturing the benefits of biodiversity and the relationships between beneficial insects to farming agriculture. Comparison testing was referenced from central Iowa, where the impacts with and without bees were measured on ten fields with honey bees versus ten fields without. Results indicated that the bees had gained colony weight while the soybeans were growing for the bees to feed on. Conversely the colony weight dropped during fallow time due to the bees feeding on honey reserves as there was no natural environment, like prairies, to feed on during the off season.

Figure 7: 2017 Allison Farms Field Day. Source: A.W. Nixon (2017)

Research performed on Allison Farms showed that a diverse mix of insect strips laced through cash crops produced a wide variety of predator insect species beneficial to crop production, by regulating pest species and also decreasing the need for insecticides. In this sense, when looking at the relationship between cash crops and pollinators it was found that even plants that do not require pollination benefit from the bee's interaction. Over 50 species of pollinators were found within the soybean fields. It was suggested that if considering utilising insect stirps, it is best to use native plants, particularly perennial plants that are deep rooted, as these provide many soil benefits and are also cost effective as they do not re-seed, eliminating the need to control any volunteer re-growth. It was further suggested that cover crop strips around the edge of harvestable crops could help by adding diversity for bees and providing added benefits of microbial activity along the edges of cash crops.

Within the trial plots at Allison Farms they had been utilising high levels of biology boosting inputs planted down with the seed, along with compost spread on at the rate of one tonne per acre, seed oil, and were ensuring dry humic was put down with all legume seeds. They have seen good establishment of cover from cow peas and indicated that chia seeds can also provide a sound level of cover. Other notable benefits from the trials included canopy closure preventing weed pressure, no pesticides were necessary, and reduced time in fields with heavy machinery meant reduced compaction.

Figure 8: Soybean crop in Allison Farms trial plots. Note the stubble cover remaining between the rows. Source: A.W. Nixon (2017)

3.1 Microbial Activity

New research indicates that soil microbes and their associated activity in the soil, are critical to soil health. A long-standing theory in the soil health realm has been the concept of increasing plant available nitrogen and this has previously been considered as one of the main functions of spreading manure to improve plant growth. However, J. W. Kinder of Kinder Farms in the USA, instigated a soil analysis of two samples taken from the Oklahoma property, after noticing a remarkable difference in the robust growth of grass from around a patch of cattle manure, despite the whole paddock having received the same level of applied urea to boost nitrogen (2017). A sample was taken from within the area containing the manure, and a control sample taken from elsewhere in the paddock. Testing was performed by Rick Haney of the United States Department of Agriculture (USDA) in Texas, on both samples, and the results proved that the most significant variable contributing to the extra leafy biomass production, was the level of microbial activity. Interestingly, the level of nitrogen from both areas was comparable.

Hoyle (2013) explains that soil microbes break down fresh plant and animal residues, absorbing the carbon and nutrients for food and growth. Throughout this feeding process they produce new compounds which can be utilised by a variety of other organisms, or they incorporate some of the carbon and nutrients into their own microbial biomass. As a result, the microbial biomass is often relative to the size of the actively decomposing organic matter fraction (Hoyle, 2011). Furthermore, exudates from living root systems are thought to be the most carbon-rich energy sources derived from plants. In exchange for this 'liquid carbon' microbes near plant roots, and those linked to plants via mycelial networks, increase the availability of minerals and trace elements required to maintain the health and vitality of their hosts (Jones, 2017). Jones asserts that all living things, both above and below the soil surface, benefit when the plant-microbe 'bridge' is functioning effectively. Hence, more so than extra nitrogen, the manure in Kinder's test samples was providing active microbial communities and additional organic residue which resulted in the vigour of the surrounding plants.

Figure 9: Author Alex Nixon, with son Archie and Mr & Mrs Kinder on their farm in Oklahoma. Source: A.W. Nixon (2017)

Trials in the Australian broadacre cropping sector have, to date, been based predominantly on single-species cover crops. While these do achieve a level of protective ground cover, the flow-on yield benefits have been minimal. This is likely due to single-species cover crops being yet another form of a monoculture. Dr Christine Jones, Australia's internationally renowned soil ecologist, claims that even adding just one or two companions into cropping scenarios significantly increases microbial activity (2017). Jones adds that "*the greater the diversity of plants the greater the diversity of microbes and the more robust the soil ecosystem*" (2017). Gabe Brown further suggests that the "magic number" is at least eight different plant species (2017). From the research as part of this report, it could be deduced that microbial activity has a generally exponential relationship to plant bio-diversity, as displayed in Figure 10 below.

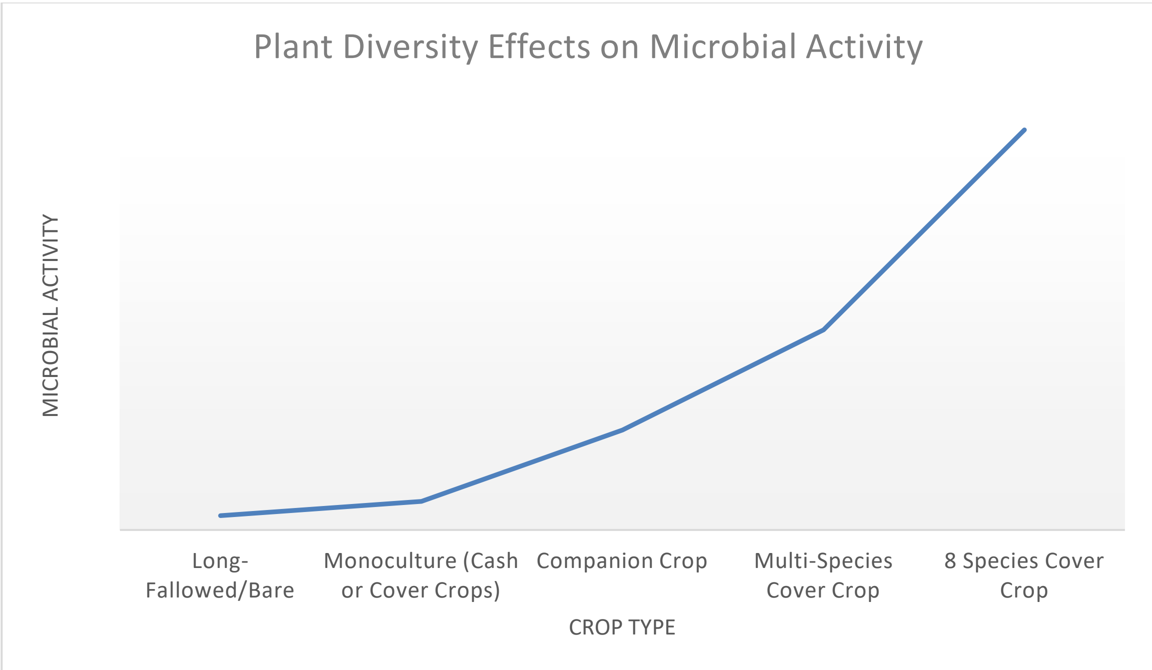

Figure 10: Plant diversity effects on microbial activity are exponential. Source: A.W. Nixon, 2017

Increasing soil microbiome is essential to soil function and can evidently be achieved through the implementation of multi-species cover crops, however balancing all soil elements is key to rapid SOM growth and overall soil health.

3.2 Fungi/Bacteria Ratio

Bacteria-dominated soil microbe populations can impede the production of SOM. This is primarily due to the fact that the bacteria are constantly feeding; mineralizing extricates of other soil microbes such as fungi (Ethridge, 2017). As the bacteria count increases, they begin to dominate the soil fungi populations, and feed faster than the fungi can supply the carbon rich extricates (Ethridge, 2017). When this happens, the bacteria move to feeding off existing organic matter within the soil, depleting reserves and inhibiting the production of SOM (Ethridge, 2017). Soil fungi populations must be increased to rectify this imbalance and moderate the diet of the bacteria.

The most successful means of growing soil fungi populations is through multi-species cover crops. Cover crops provide living roots which create symbiotic relationships with fungi (Ethridge, 2017). Different types of mycorrhizal fungi can be found on almost 90% of the worlds' plants (Ethridge, 2017). Jones (2017) states that for a crop to access water and a wide variety of trace elements and nutrients, "*vigorous root systems and beneficial relationships with mycorrhizal fungi and other plant-associated soil biota are essential*". When a diverse range of living roots exist within the soil, a complex give-and-take relationship ensues. Roots provide carbohydrates to mycorrhizal fungi, which in turn provides water and nutrients from the soil profile to the roots (Ethridge, 2017). The fungi then release extricates and sugars which feed the soil bacteria (Ethridge, 2017). The bacteria subsequently provide nutrients to the mycorrhizal fungi which can then be passed back to the living roots (Ethridge, 2017). The result is a more balanced ecosystem. This notion is further supported by Gabe Brown's perception that the desirable fungi/bacteria ratio is close to 1:1 (2017). Cover mixes containing grasses, broadleaves and legumes together, appear to maximize both the quantity and diversity of mycorrhizal fungi populations (Ethridge, 2017).

3.3 Carbon/Nitrogen Ratio

Plant diversity in a multi-species cover crop is necessary to ensure that a moderated supply of actively decomposing organic matter is available over time through varying levels of C:N ratio within differing plant species. Plant material contains approximately 45% carbon, and depending on the residue type, anywhere from 0.5-10% nitrogen (Hoyle, 2013). This ratio of carbon to total nitrogen reflects how readily organic matter decomposes, and further indicates the rate and amount of nitrogen release that might be expected from decomposition (Hoyle, 2013). The C:N ratio of organic inputs also influences the amount of plant available nitrogen in the soil. Organic residues with between 25:1 and 30:1 ratios have sufficient nitrogen levels available for microbes to be able to decompose them without relying on soil nitrogen stores (Hoyle, 2013). Residues with a lower C:N ratio (<25:1) such as legumes, will generally result in accelerated decomposition of organic residues and tend to contribute to plant-available nitrogen levels, while plants with a higher ratio (>30:1) such as cereals, decompose more slowly and result in less plant-available nitrogen being released (Hoyle, 2013).

The rate of decomposition of organic residues is also relevant to the longevity of the changes in soil properties. One example is soil aggregate stabilisation. Stabilisation of aggregates is a function of existing physical forming forces in soil to form aggregates, together with the release of aggregating agents from soil microorganisms upon decomposition of organic materials (Martens, 1999). Generally, quickly decomposing residues will exert a rapid stabilisation of soil aggregates, which is transient (Martens, 1999). Contrarily, materials with a slower decomposition rate take longer to achieve maximum aggregation, however the effect on aggregation is longer-lasting (Marten, 1999). The C:N ratio and the decomposition rates of various plants also has a relative impact on the cycling of carbon and nutrients, which is moderated by the associated microbial activity.

3.4 Carbon/Nutrient Cycling

Soil microbes and microorganisms play an important role in both the carbon and nutrient cycles, all functions of which are well supported by the introduction of a species-rich environment. Carbon cycling refers to the biogeochemical exchange of carbon between the Earth’s atmosphere, geosphere, hydrosphere, biosphere and pedosphere, with soil holding the largest portion of the Earth’s active carbon (Corning et al, 2016). Plants take carbon from the air and convert it into plant tissues, through the process of photosynthesis (Corning et al, 2016). Carbon is transferred to the soil through plant root respiration, where it is either stored, or released back into the atmosphere by soil respiration. Additionally, as the residues from plants decompose, the carbon, nitrogen and phosphorous (P) compounds, unavailable yet to plants, are consumed by microbial communities for food and growth (Haney, 2017). Excess nitrogen and phosphorous is released by the microbes in a plant-available form, together with carbon dioxide which is released through microbial respiration (Haney, 2017).

Species richness has proven to be directly correlated to microbial biomass growth and activity associated with root biomass production, and subsequently, higher levels of soil carbon storage. In a nine-year experimental field study, Lange et al (2015) found that higher plant diversity increased carbon input into microbial communities within the rhizosphere (narrow region of soil that is directly affected by root exudates and soil microorganisms), resulting in greater microbial activity and increased carbon storage. The results of the experiment indicated that the storage of carbon in soil is governed by the metabolic activity of microbial communities, which is mediated by plant diversity via higher root inputs (Lange et al, 2015). A number of processes were found to influence microbial activity through species richness, these are summarised in Table 3.

Process	**Influence**
Denser vegetation in highly diverse plant communities.	Evaporation reduced from topsoil which in turn promotes higher microbial activity and growth.
Soil carbon storage, linked to root inputs including root exudation	Known to change activity and composition of microbial communities.
Increased diversity of soil microbial communities	Increased microbial respiration.
Shift in metabolic activity of microbial communities towards anabolic activity	Increased necromass accumulation over time.

Table 3: Processes affecting microbial activity (A.W. Nixon, 2017)

The increased microbial products and necromass end up in slow-cycling SOM pools in the form of reduced organic material, suggesting that the activity and composition of microbial communities could serve as a segue for carbon transfer into sustainable, slow-cycling forms of soil carbon (Lange et al, 2015). The effect of plant diversity on these processes, and the associated microbial changes, can significantly contribute to the sequestration of atmospheric carbon dioxide (Lange et al, 2015).

Chapter 4: Financial Viability of Cover Crop Rotations in Broadacre Dryland Farming

Optimal soil health is unequivocally important to broadacre cropping in order to produce a sustainable and financially viable farming future. Multi-species cover crops are irrefutably the ultimate method in rejuvenating and maintaining ideal soil conditions, yet broadacre dryland farming businesses face a number of issues when moving towards such conservation management practices. Firstly, upfront costs of cover crop seed currently remain exorbitantly high. Machinery investments, such as rollers, mowers or crimpers are costly and not yet readily available in Australia. The logistical implications associated with the scale of Australian farms could incur increased expenses. And finally, business cashflow can become compromised if input costs to establish the cover crop exceed the expected returns for the season. This chapter will explore these concerns, in conjunction with some suggested actions and countermeasures.

Case Study: Overbury Farms

Overbury Farms in England is part of the family owned estate Overbury Enterprises and covers 1,565 hectares of Cotswold arable land, surrounding the villages of Overbury and Conderton on the Worcestershire and Gloucestershire borders. The farm produces sheep, alongside cash crop rotations which include wheat and green peas and more. The author met with farm manager Jake Freestone who indicated that the family enterprise is operated with an emphasis on conservation and longevity with a strong intent to share the farm with future generations. The farm currently meets the rigorous environmental standards of the Linking Environment and Farming (LEAF) marque, which is a farm assurance system in the UK showing that food has been grown sustainably with care for the environment. This is in addition to their own farm assurance standards, and in late 2012 Overbury Farms became a LEAF demonstration site.

Over the past three years, Freestone has been experimenting with companion cropping based around legumes to increase the capture of atmospheric nitrogen and make it available to the farming system. He stated that the atmosphere is 76% nitrogen, yet cereals and brassicas are unable to access it, while legumes can. He has also been incorporating multi-species cover crops into cash crop rotations for several years, which are fed off to sheep, adding further biological benefits to the soil from manure.

Freestone stated that Overbury Enterprises were economically able to make the change to conservative, sustainable farm management practices through their off-farm trading activities which consist of:

- Home property rental.
- Other farm services and contracting.
- Training, meeting and workspace rentals.
- Early years nursery and out of hours school club.
- Luxury farmhouse holiday rental.

Figure 11: (L) Author Alex Nixon with Overbury Farms manager Jake Freestone, England. (R) Crop of green peas on Bredon Hill, Overbury Farms, England. Source: A.W. Nixon, 2017

Case Study: Green Fields Farm

Green Fields Farm is a fourth-generation farm in Rogers, Texas. The author met with current owner-operator Jonathon Cobb for a tour of the farm where in recent years they have been making the shift towards regenerative agriculture. Jonathon explained that prior to his management, the farm was operated under a stereotypically integrated system of grain crop rotations and multi-species animals, utilising large equipment and many inputs to harvest monocultures of corn, cotton, wheat and sorghum. He commented that after five years of being back on the farm himself, he realised that a change was necessary. The flawed system under which they were operating, was one of the catalysts for change. He stated that three of the five years were the worst his father and predecessor, had witnessed. They were increasingly adding more inputs with little to no improvement in yield.

In 2013 they formed Green Fields and began the transition towards becoming a regenerative multi-species pasture-based farm, incorporating holistic management practices with a focus on soil health. As part of their vision for change, Cobb’s decided to liquidate most of their heavy cropping assets and machinery. These funds helped to sustain the business through the transition period until pastures had been established and herd numbers had been increased. They now grow multi-species covers, improved multi-species pastures and fodder crops of forage sorghum, maze, millet and beans, which are rotationally grazed with cattle and sheep.

Their current business model is dedicated to local markets to reduce the collective footprint of the farm and increase industry transparency, emphasising the importance of consumers understanding where and how their food is produced. They farm using methods designed to increase soil health, conserve water, protect the environment and create an ecosystem in which plants and animals thrive.

4.1 Logistics and Considerations

The majority of research, trials and recommendations for implementing cover crops currently stem from the USA. When considering applying this knowledge to Australian broadacre cropping arrangements the information must be adapted, though many of the basic theories remain the same. Factors for consideration include, but are not limited to:

- Climate.
- Soil type.
- Current management practices.
- Existing cropping schedules.

Licht and Kasper (2015) suggest that when looking to transition into cover cropping, it is important to start small, and increase scale gradually. This reduces the initial risk and time required for cover crop implementation. Selecting small or irregular paddocks, or sections of paddocks that are prone to erosion and/or nutrient leaching is a recommended starting point (Licht and Kasper, 2015).

Logistically, there are two main components to effectuating a cover crop: Planting and Termination. Table 4 below lists some relevant constituents of each, worth considering before implementing a cover crop rotation.

Planting	Terminating
• Seed Selection/Species Mix • Method – Aerial/Planter • Seed Rate • Timing • Depth (if using a planter)	• Timing • Method – Mower/Roller/Crimper/Herbicide

Table 4: Planting and Termination Methods (A.W. Nixon, 2017)

4.2 Species Selection

Species selection is perhaps the most important element to successful cover cropping. Several factors must be considered when choosing a cover crop mix, being:

- **Current soil conditions** – soil testing prior to seed mix selection is advisable to establish what functions are required and thus which species can best fulfil the requirements.
- **Subsequent cash crop** – it is important to keep this in mind to avoid any potentially negative impacts from undesirable soil changes or pathogenic species to the following crop. Varieties selected must be compatible together, and with the subsequent cash crop.
- **Seasonal and climatic conditions** – rainfall, temperatures and time of year should all be considered when choosing each variety for a multi-species cover.
- **Plant functional group** – a selection of cereals, grasses, legumes, brassicas and chenopods is recommended for optimal soil health benefits.

Table 5 lists some commonly recommended cover crop species (sorted by functional groups) and their associated benefits and preferred conditions. It is important to note that specific benefits can vary in capacity from species to species, the benefits listed below are general per functional group only.

Functional Group	Benefits	Species	Preferred Conditions
Cereals	-Scavenging nutrients (especially N). -Reducing or preventing erosion. -Producing large amounts of residue contributing to SOM. -Weed suppression.	Rye	-Light loams/sandy soils. -Soil pH 5.0-7.0. -Minimum Germination Temperature (MGT) 1.1°C.
		Wheat	-Well-draining, moderately fertile soils of medium texture. -Soil pH 6.0-7.5. -MGT 3.3°C.
		Barley	-Well-draining fertile loams or light, clay soils. -Soil pH 6.0-8.5. -MGT 3.3°C.
		Oats	-Moderately fertile soil. -Soil pH 4.5-7.5. -MGT 3.3°C.
Grasses	-Scavenging nutrients (especially N). -Reducing or preventing erosion. -Producing large amounts of residue contributing to SOM. -Weed suppression.	Ryegrass	-Fertile, well-draining loam/sandy-loam soils. -Soil pH 6.0-7.0. -MGT 4.4°C.
		Sorghum-Sudangrass	-Warm, moist, fertile soils. -Tolerates low-fertility/moderate acidity/high alkalinity -Soil pH 6.0-7.0. -MGT 18.3°C.
Legumes	-Fix atmospheric N. -Reducing or preventing erosion. -Producing biomass for SOM. -Attracting beneficial insects. -Alleviate soil compaction.	Crimson Clover	-Well-draining soils particularly sandy loams. -Thrives in cool, moist conditions. -Soil pH 5.5-7.0.
		Hairy Vetch	-Moist conditions. -Soil pH 5.5-7.5. -MGT 15.6°C.
		Field Peas	-Well-limed, well-draining clay or heavy loam soils. -Soil pH 6.0-7.0. -MGT 5°C.
		Red Clover	-Well-draining soils. -Soil pH 6.2-7.0. -MGT 5°C.
		White Clover	-Clay and loam soils. -soil pH 6.0-7.0. -MGT 4.4°C.
		Various Medics	-Reasonably fertile, neutral soils. -Lower moisture.

			-Soil pH 6.0-7.0. -MGT 7.2°C.
		Sweet Clover	-Neutral loam soils. -Soil pH 6.5-7.5. -MGT 5.6°C.
Brassicas	-Scavenging nutrients. -Reducing or preventing erosion. -Alleviate soil compaction. -Weed suppression. -Soil borne pest suppression. -Biofumigation activity. -Cold-hardy. -Drought-tolerant.	Turnip	-Well-draining soils. -Soil pH 6.0. -MGT 10°C.
		Radish	-Well-draining soils. -Soil pH 6.0-7.5. -MGT 7.2°C.
		Rapeseed	-Well-draining soils. -Soil pH 5.5-8. -MGT 41°C.
Chenopods	-Creates synergistic root response. -Plant roots begin exuding Phenolic Compounds. -Fast-tracks benefits/soil changes from other plants.	Spinach	-Rich, well-draining soils. -Soil pH 6.5-7.0.
		Swiss Chard	-Rich, Well-draining soils. -Soil pH 6.0-6.8.

Table 5: Plant Species Benefits/Conditions Per Functional Group (adapted from SARE, 2012, Bonnie Plants, 2017, Sait, 2017).

4.3 Financial Viability

The effectiveness of incorporating cover crop rotations for rejuvenating and maintaining soil has been substantiated in many farming situations around the globe. Research for this report were conducted on several properties in the USA and England, with notable success in restoring soil health recorded at each. However, one common concern was the financial viability while transitioning to this management practice. A business, or business decision, is considered financially viable when generated income sufficiently meets payment demands.

Multiple farming operations visited in the USA and England reported experiencing financial deficits in the initial cover cropping seasons. Jonathan Cobb from Texas, USA indicated that consolidating and monitoring input costs, plus decreasing capital invested in plant and machinery had been contributing factors to their ability to transition into cover cropping (Cobb, 2017). Similarly, Overbury Farms in England, managed by Jake Freestone, is part of a large estate. Freestone stated that conservation of the soil for future beneficiaries had been prioritised over the cashflow and turnover of the farming enterprise during the instigation of cover cropping rotations, and was readily subsidised by other Estate incomes until the financial benefits of the new practices came into effect (Freestone, 2017).

Another important point worth noting regarding the above examples, is the relative size and scale of the business. Some of the farms visited were as small as 600 acres (approximately 243 hectares), while the average farm size in Australia is 4,331 hectares (Australian Bureau of Statistics, 2017). Appropriating business funds for cover-cropping to such a scale as to fit the average Australian farm, could initially pose the following issues and risks:

- Increased upfront costs for seed and planting.
- Compromised business cashflow.
- Time allotted for planting/termination could result in the necessity for multiple machines to be operating to achieve the task within ideal timeframes, resulting in more business funds being absorbed by capital investments.
- Soil types can vary dramatically from one end of a largescale paddock to another, impacting cover-mix selection and effectiveness.

Some suggestions to alleviate and manage these problems are to:

- Start small – one paddock at a time.
- Consider frequency and size of cover rotations based on benefits produced, and increase accordingly over time.
- Consider value-adding - Controlled grazing of cover crops can provide extra income/soil benefits over the cover-crop season. Investing in livestock or offering short-term agistment are two potential options.

While some financial difficulties may arise when farming operations initiate cover-crop rotations, the long term monetary benefits are purportedly profitable. Some economic benefits may be seen within the first year, and the business 'bottom line' can increase more over the years as the soil-improving effects accumulate (SARE, 2012). Some of the economic benefits of multi-species cover cropping are:

- Decreased fertiliser costs.

- Reduced requirement for herbicides and pesticides.
- Higher yields – due to improved soil health.

Figure 12 and 13, taken from Freestone's operation in England, depict how the benefits of active, living soil can positively impact a subsequent cash crop.

Figure 12: Active, living soil, including earthworms, from a cover crop plot on Freestone's farm in England. Source: A.W. Nixon (2017)

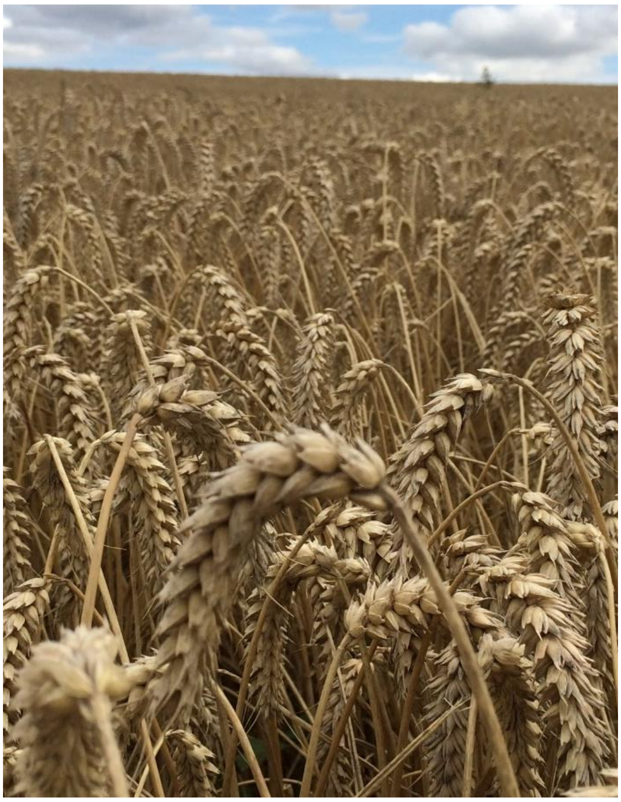

Figure 13: Healthy wheat following a cover crop, is expected to yield substantially well. Source: A.W. Nixon (2017)

Conclusion

The sustainability of Australian broadacre dryland cash cropping operations, and the agricultural industry in general, hinges heavily on a soil health focus. Incorporating multi-species cover crops into cash crop rotations is the most effective way to improve soil health.

The evidence presented in this report proves that multi-species covers can alleviate several environmental factors affecting soil health by:

- reducing or preventing erosion.
- increasing water infiltration.
- inhibiting weed growth.
- increasing SOM.

Further, this report emphasises the importance of bio-diversity within a cover crop, showing how a species-rich environment creates synergy between all soil components. Bio-diversity encourages:

- effective carbon and nutrient cycling.
- a balance of C:N ratios.
- microbial growth and activity.
- healthy bacteria to fungi ratios.

Though implementing diverse cover-crops can pose initial economic issues, the long-term environmental and economic benefits prove to outweigh the financial deficit associated with the transition phase. Through careful management and mix-selection, multi-species cover cropping can certainly be a viable option for Australian broadacre farmers seeking to improve soil health.

Recommendations

- Employ zero-till farming practices wherever possible to lessen soil degradation.
- Create a cover crop rotation schedule – based on soil test results and current cash crop rotations. It is imperative to have a plan, goal and strategy in place in order to be effective and efficient in any business venture.
- Implement a business plan for the transition phase – expect that multi-species cover-cropping is a long-term investment, interim alternative income sources may be required to support the associated expenditure.
- Conduct regular soil testing – knowing your soil and monitoring soil changes will ensure that appropriate actions can be taken e.g. which paddocks require attention, what soil health issues are arising, and which plant species are most suited for rectification.
- Research plant varieties suitable for the region – understanding species for both their benefits and their required growing conditions is advisable. Consider contacting a local agronomist if necessary and remember, the more species the better!
- Construct a "seed budget". Seed will be the primary input cost. Pricing different varieties and options available and adhering to a budget will minimise any negative financial impacts in the initial season.
- Decide which methods will be employed for planting and termination – performing an opportunity cost analysis may assist when considering alternatives.
- Consider value-adding (such as livestock grazing). It is important to closely monitor and control any grazing to ensure the best results from plant growth benefits.
- Encourage neighbours to get involved – a local cooperative initiative could be an option for capital investment of plant and machinery, bulk seed purchases to obtain discounts and disseminating local knowledge, information and findings from trials.
- Consider applying for government grants and subsidies associated with agricultural conservation practices.

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Plain English Compendium Summary

Project Title: Farming For the Future	**Name of project: Optimising Soil Health for a Sustainable Future in Australian Broadacre Cropping**
Nuffield Australia Project	1709
Scholar:	Alexander Nixon
Organisation:	Bexa Pty Ltd T/A Devon Court Stud 769 Wallan Creek Road DRILLHAM, QLD, 4424
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Objectives	- Research organisations and farmers trying to improve soil health across the world. - Gather information from research facilities in the USA investigating soil health and the relevant contributing factors thereof. - Investigate farmer implementation of cover crops and regulated grazing to improve organic carbon levels in both England and the USA. - Establish how this information can be applied in a broadacre dryland cropping scenario, with specific consideration to the logistics and financial viability of incorporating cover crops into cash crop rotations in Australia.
Background	For many years conventional farming practices have been degrading the state of our soils. The zero-till farming revolution has instigated a push towards improved soil health. New research indicates that bio-diversity and groundcover are essential contributing factors to optimal soil health, and many farms in the USA and England have been implementing multi-species cover crop rotations in conjunction with zero-till practices with amazing results in soil rejuvenation and increased cash crop yields.
Research	Soil function and the benefits and considerations for incorporating multi-species cover crops into Australian broadacre cropping regimes. Research was conducted in the USA and England, but also in Brazil, Chile, Canada, Italy and the Netherlands, through a combination of interviews, meetings, conferences, field days and farm tours, together with personal studies.
Outcomes	Incorporating multi-species cover crops is the most effective and efficient means to improve soil function and health. Multi-species cover rotations are a financially viable option for Australian broadacre cropping operations seeking to improve their soil and reap the subsequent benefits through increased cash crop yields. Careful planning and management of the rotation schedule and seed-mix selection is required to obtain optimal benefits.
Implications	This report explains the benefits of using multi-species covers as ground cover to suppress weeds, reduce erosion, increase soil organic matter and improve water infiltration/moisture retention. It also describes the changes within the soil ecosystem associated with maintaining bio-diversity, and provides some information and considerations relevant for implementing multi-species cover crops in broadacre cropping rotations in Australia.
Publications	Nuffield Australia National Conference, Melbourne, September 2018.