CHAPTER 1
INTRODUCTION

As a partner on a dry land cropping farm, my interest to undertake a detailed research project to investigate aspects of no-till farming arrived out of a series of visits (starting in 2000) to agricultural properties and research stations around Australia and in other parts of the world. During that time I met many researchers and farmers that had either researched or adopted no-till agriculture. This meant that they abandoned mechanical soil cultivation and were using herbicides for weed control. Some were also growing cover crops to increase surface soil residues, which they claimed helped them to not only improve the conditions of their soil, but to also reduce their reliance on herbicides. The people that we have met over the years highlighted the many benefits and changes to soil properties, crop production and to environmental outcomes due to their uptake of no-till. The reasons for adoption were variable, as was the range in benefits and disadvantages that they encountered.

Some of the areas visited during these trips included Canada and Ukraine, where winter snow fall events can be variable and the adoption of no-till had allowed more snow to be trapped by the undisturbed standing stubble. Aside from the additional moisture benefits, the increase in snow cover gave an insulating effect reducing the level of soil freezing. The side benefit of this had been the ability to direct drill earlier in no-till soil compared to cultivated soil. Alternatively winter wheat is planted before the snow season and left to become dormant during winter and the crop is covered with snow. After the snow melts in spring the crops come out of dormancy. The risk to this practice is 'winter-kill' caused by low snow falls or late season frosts when wheat is coming out of dormancy. Many farmers said that they noticed that because standing stubble in no-till paddocks trapped more snow, the risk of winter- kill was reduced when they converted to no-till agriculture. They also stated that the practice of no-till in these regions had not only reduced the risk of crop loss but it had increased yields and allowed flexibility in cropping time and the type of crop grown, enabling no-till farmers to adapt to changing marketing conditions hence becoming more profitable.

In areas such as parts of South America and Queensland, Australia there can be a high frequency and high amounts of rainfall that can cause severe gully erosion if the soil is cultivated, particularly in undulating landscapes or it can cause sheet erosion in other landscapes. The adoption of no-till agriculture in areas such as these had meant that soil erosion and loss of valuable topsoil had been reduced. The added environmental advantage is the reduction of silt building up in rivers and estuaries caused by soil loss from cultivated soil. The long term effect of silt accumulation was witnessed at Ephesus in Turkey where the Ephesus Bay that was once used as a commercial harbour in Ancient Roman times is now farmland due to a slow accumulation of soil deposited into the bay from surrounding cultivated land over a period of 2000 years.

In areas of the world where there are high wind events such as Western Australia and parts of China no-till agriculture had shown the benefit of reducing soil loss. Standing stubble in these areas had been shown to act as a barrier and reduced the damaging effects that wind can cause on bare cultivated soil. The retention of valuable top soil is top priority for many farmers that I had visited as they not only see it as an environmental issue but also an economic one. Nutrients must be replaced if they are removed either by gully, sheet or wind erosion.

In areas such as northern NSW and southern Queensland in Australia as well as in Botswana where the rainfall is not only variable but often summer dominated when evaporation rates are high, the adoption of no-till had improved the yields of both summer and winter crops due to the ability of no-till soils to retain more moisture than cultivated soils. In particular the adoption of no-till in drier areas around Nyngan, Walgett and Coonamble in New South Wales, Australia have enabled annual crop production to increase because of the increase in the retention of stored soil moisture allowing these farmers to be less dependent on rain during crop growth compared to when the land was cultivated. This has resulted in some of these areas now becoming very desirable cropping areas.

While I have witnessed all these successful stories by farmers and researchers in the various parts of the world and observed the associated passion and enthusiasm for the practice of no-till agriculture, there were pockets in the world where the uptake was less extensive. These regions included parts of England, Europe and South Africa as well as some mixed

farming areas in NSW Australia. In many of these areas the climate is relatively more stable and there are less production risks and soil erosion is not perceived as important. In some high population density European countries, the associated use of herbicides was seen as a disadvantage of no-till agriculture as the use was perceived as a risk to human health. At one soil conference in Germany, in 2006, an off the record comment from a government official even hinted that the European resistance to no-till agriculture is linked to the perceived benefit that American multinational companies make by having farmers becoming dependant on herbicides. This is despite the fact that there are many European companies involved in the manufacture and sale of cropping herbicides.

In areas such as Vietnam and China, that were visited in 2004, either the lack of commercial inputs or lack of the agronomic advice on which products and appropriate rates to use in particular circumstances, was considered a disadvantage to the uptake of no-till. At one round table conference a Chinese researcher expressed the concern about allowing farmers access to herbicides due to possible environmental and human health side effects. Even in Australia I have attended farmer talks that suggest that the practice of using herbicides, which have been an important part of the no-till revolution, are the cause of reduced soil biological properties so should be avoided.

The environmental, productivity and profitability benefits and hence uptake of no-till appear therefore to depend on the location, climate and production risks of the farm as well as the belief system of individual farmers and their society. The result is that either no-till had been adopted by farmers with great gusto and zeal or had not. While it is important to acknowledge the great advantages of no-till agriculture and admire the enthusiasm of adoptees it is important to acknowledge other points of view and to monitor possible disadvantages of no-till that might possibly lead to a future system collapse.

A past example of agricultural collapse is the famous “dust bowl” event in America during the 1930’s which mainly was caused by the over enthusiasm of croppers to adopt the then recent innovation techniques of wide scale mechanical cultivation of the soil to improve crop production. Those practices however appear to be unsustainable especially in times of reduced rainfall or long periods of drought. While in Texas in 2011 one farmer told me that the then present drought was as bad as the one in the 1930’s but because most croppers were now no-tilling there was not the environmental damage caused by dust storms as had

occurred previously. It is not known if the long term and widespread use of no-till agriculture has similar hidden negative outcomes. It is imperative that researchers and proactive farmers monitor the practice of no-till farming to identify and propose solutions to possible leaks in the no-till system that might accumulate over time and if not corrected may have not just undesired consequences but may also lead to a similar system collapse as that which occurred in Texas in the 1930's.

One possible threat to the no-till system was investigated by Bell *et al*. (2006). They identified reduced C and microbial biomass in no-till cropping systems as practiced in southern Queensland, Australia. They linked this reduction to the practice of including long fallows as part of the zero till cropping rotation. The long period without plant growth appeared to be detrimental to soil biological properties and to the level of soil C. The possible reduction in soil C is an important issue as Australia moved into a low C economy based on the introduction of a carbon tax in July 2012. The reduction in soil biology has important ecological as well as possible production issues. It is important to look at other regional areas of Australia to investigate whether this is a potential leak or if it is just localised to southern Queensland. It is also important to determine if it is possible to be proactive, rather than reactive to this potential threat or other threats that might be also be indentified.

Another important Australian cropping area is the CW NSW that is worthy of investigation for potential threats to the sustainability of no-till agriculture. While it has been identified as a region where no-till adaption has been slower than other areas of Australia it is estimated that about 70% of farmers in CW NSW practice no-till (LLewellyn and D'Emden 2010). It has been identified as a region worth investigating as it produces about 20% of wheat produced in NSW (Australian Bureau of Statistics 2011). It is important that no-till agriculture can be continually practiced to maintain environmental protection while allowing highly productive crops to be produced for the profitability of farmers and the community that relies on that income.

This study was undertaken to investigate some of the issues relating to no-till farming within the CW region of NSW Australia. The project was funded by the Grains Research Development Corporation (GRDC), and some soil testing was also funded by NSW Central

West Catchment Management Authority (CW CMA) and Macquarie 2100 through a grant from the National Land care Project (NLP). The outcomes of this research would help a no-till farmer make informed decisions on some possible side effects of the current practice of no-till and how to rectify that in a cost effective manner. The specific aims of this project are:

1. Identify any possible changes in the physical, chemical and biological properties of no-till cropping soil within the CW NSW.
2. Determine what effect certain surface applied amendments have on physical, chemical and biological properties of a long-term no-till cropping soil within CW NSW when no plants are actively growing, as in a long fallow situation as well as when wheat is actively growing in the soil.
3. Determine the short term biological effect of different rates of the most effective amendment in improving soil biological properties.
4. Economics of adjusting management to improve soil biological properties.

This thesis structure starts with Chapter 2 providing relevant background information about issues facing no-till farmers and in particular the benefits of having a healthy and diverse micro-biological soil. Chapter 3 investigates physical, chemical and biological soil properties of various clay cropping soils of both high and low productivity which are currently managed under no-till agricultural methods within the CW region of NSW. Chapter 4 describes the results of a field trial established on clay soil within this region to examine the effects of organic amendments on soil properties both in a long fallow situation as well as during wheat production. Chapter 5 describes the short term effects that the rates of barley mulch levels have on the soil microbial, bacterial and fungal biomass levels. Chapter 6 applies an economic analysis to determine opportunities that no-till farmers might have to increase the level of soil C and SMB C, in particular its fungal biomass component. Chapter 7 presents general conclusions and outlines directions for future research directions.

CHAPTER 2
REVIEW OF LITERATURE

2.1 INTRODUCTION

While crop productivity is an important issue in terms of food security there are many other soil related issues that soil scientists and farmers need to address. Lal (2007) argued that some of these pressures include mitigating global warming, improving quantity and quality of freshwater resources, enhancing biodiversity, minimising desertification, and meeting growing energy demands as well as using the soil as a repository of waste. Management practices that may address some of these issues may be restricted by the demands for profitable outcomes. Many farmers have adopted conservation farming systems in the belief that this will give them many of these desired outcomes as well as increased productivity, especially in times of variable or adverse environmental conditions (Bamforth 1988).

Terminologies used in conservation farming practices are often localized and, at times tend to be contradictory. In Europe, the term "conservation tillage" describes soil management practices that tend to minimize the disruption of the soil's structure, composition and natural biodiversity (Holland 2004). Just one reduction in a tillage operation would be classed as conservation tillage under this definition.

Many use the terms "conservation tillage" and "conservation agriculture" interchangeably. The term "conservation agriculture" however is also used to describe a whole system which does not include any soil disturbance, other than that done at sowing, and is in synergy with good management of crop residues and the rolling of cover crops, so offering a permanent soil cover (Guedez 2001). Cover crops are defined as "any living ground cover that is planted into, or after a main crop and then commonly killed before the next crop is planted" (Hartwig and Ammon 2002a).

Early forms of conservation tillage in Australia were in the form of direct drilling, which is the process of seeding without prior cultivation, which usually follows the application of herbicides to kill all plant growth (Mason and Fischer 1986). Direct drilling can involve

complete disturbance into retained or burnt stubble but is also used to describe the seeding process of the no-tillage systems that retains stubble on the surface. Different types of drills are used, such as heavy discs for cutting narrow drills, or strong cultivator tynes (Stephens 1996). Derpsch (2005) argued if planting technology that seeds into unprepared soil that involves any kind of surface or subsurface tillage (with sweeps or tynes) that covers most or the whole width of the seeding machine, cannot be termed no-tillage.

In Australia, the term no-tillage is commonly used to describe the system that uses tynes to plant into retained stubble, which only disturbs the soil within the sowing row. The term 'zero tillage' is used to describe the seeding process using disc type openers that place the seed without any surface soil disturbance (Southorn *et al.* 2004). This review will refer to the Australian convention of no-till and will treat zero-till as a similar practice. This definition does not take into account the type or amount of retained crop residues.

The aim of this review is to examine some of the environmental and ecological issues facing cropping farmers using the Australian no-till farming system. The main environmental issues addressed here are climate change, soil sustainability and soil biodiversity. In particular, the types and ecological role of micro soil organisms will be investigated. The features, benefits and disadvantages of no-till will be discussed. The use amendments is investigated to assess if these might have a place in Australian no-till farming systems to overcome some of the possible environmental and ecological disadvantages that may be associated with the common current Australian practice of no-till farming and hence aid in the increase of the up-take of no-till regimes, especially in areas like CW NSW.

2.2 CLIMATE CHANGE

Global warming is seen as a substantial threat to human populated areas and to food-producing regions which are vulnerable to drought, as well as being a cause of natural disasters arising from extreme weather (Grace 2004). Global warming is thought to be caused by the increasing levels of atmospheric gases such as carbon dioxide (CO_2), methane and nitrous oxide that trap heat at the earth's surface and increase global temperatures (Krebs 2001). While there are many sources of increasing levels of these gases, agriculture is one of the major contributing factors as the loss of C to the atmosphere from deforestation and other land-use activities has been greater through the past 300 years

than has the gain from enhanced photosynthetic uptake of C by increased fertilizer use and increased atmospheric CO_2 (Ver Mackenzie and Lerman 1999). Soils hold more C than the atmosphere (Novak *et al.* 2009) and the soil C pools include the litter layer, charcoal, soil organic C and inorganic C (e.g. carbonates) but it is the changes in soil organic C that is the major influence of atmospheric C (Batjes 1996) and there has been a mass loss of organic matter reservoirs (humus) that has decreased the C in the soil and increased it in the atmosphere (Ver Mackenzie and Lerman 1999). It has been estimated that cultivation of the soil, in the tropics, has contributed to as much as 20% to the recent increase in atmospheric CO_2 concentration (Lal 2004)

Despite the overall upward trend in CO_2 levels in the atmosphere since 1750 and the start of the industrial revolution there are seasonal atmospheric oscillations resulting from seasonal uptake of CO_2 by plants via photosynthesis, seasonal differences in fossil fuel use and CO_2 exchanges with oceans (Krebs 2001). CO_2 is produced in soils by roots; soil organisms and chemical oxidation of C-containing materials (Raich 1992). Soil respiration rates are positively correlated with mean average temperatures and mean annual precipitation. The estimate of soil C turnover rates range from 500 years in tundra and peaty wetlands to 10 years in tropical savannas (Raich 1992). While tree planting is often advocated as one way for farmers to sequester C (Grace 2004), changes in some cropping and soil management practices may also be needed to sequester more C and to slow the rate of soil C turnover as well as adapting to the possible detrimental consequences of climate change (Lal 2004).

2.3 SOIL SUSTAINABILITY

Farmers rely on the fundamental properties of soil to produce crops. In recent years, there has been a strong reliance on synthetic inputs to try and improve the quality of the soil to grow more productive crops. There seems to be a growing concern about the sustainability of some of these inputs due to unknown effects on the soil biota and the possibility that they may become more expensive due to the their finite source in times of peak oil as well as adding greenhouse gases to the atmosphere either through their production, or volatilization when applied to the soil. Smith and Powlson (2007) define soil management sustainability as that which “meets the needs of the present without compromising the ability of future generations to meet their own needs from that soil”. Yachi and Loreau (1999) suggested that the management practices that threaten the soil biological

community may also threaten the capacity of the soil to adapt to future changes. A review by Brussaard, de Ruiter and Brown (2007) found that both soil and above ground biodiversity is needed to sustain agro-ecosystems. They concluded that early research is indicating that soil biodiversity gives the soil the ability to suppress diseases, confer resistance and resilience against disturbance and stress as well as possibly being correlated to stable soil community structure.

Doran and Parkin (1994) maintain that a healthy soil should sustain biological productivity, promote plant and animal health while maintaining environmental quality. Doran & Zeiss (2000) defined the term 'soil health' to portray soil as 'a living, dynamic system whose functions are mediated by a diversity of living organisms that require management and conservation' and they used the term 'soil quality' synonymously with it. In their paper, they argued that the challenge is to develop agricultural management systems that balance the needs for food and fibre production with those for the maintenance of the environment. Coleman (2008) further claimed that the term "soil health" should specifically include the healthy activity of all organisms including micro-organisms.

The current understanding of the role of soil micro-organisms in sustainable production systems is limited (Coleman *et al.* 2004). Sylvia *et al*. (2005) explained that the reason for this was that the soil microbial habitat was the result of complex interactions between the soils physical properties (bulk density, particle density, and pore spaces), chemical properties (including pH, anion and cation exchange capacity), soil abiotic factors (soil water, soil aeration and soil temperature), soil micro-organisms, and living and dead plants. They further explained that the soil habitat is extremely variable due to this interdependence and as a result some micro-organisms will grow, others will die, some microbial processes will begin and others will stop all within a cubic millimetre of soil. This has resulted in the evolution of a diverse range of organisms within soils with resulting complex interactions and community structures.

2.4 SOIL BIODIVERSITY

Soil micro-organisms have great metabolic diversity, exhibiting all forms of metabolism and life strategies needed to acquire energy and nutrients to meet their needs of growth, survival, and reproduction (Sylvia *et al.* 2005). This diversity allows life in the soil to

continue when energy, nutrients, temperature and moisture levels fluctuate or change. The number of soil micro-organisms is immense. There may be as many as ten thousand to one million different species of bacteria (Sylvia *et al.* 2005) and over 70 000 species of fungi that have been described but there may be as many as 1.5 million species in existence (Coleman *et al.* 2004). The current knowledge of the range of organisms in the soil is low and so it is impossible to affix a numerical value to any losses that may have occurred (Coleman 2008). While the functions of soil organisms include degradation of organic matter, cycling of nutrients, sequestration of C, production and consumption of trace gases, degradation of water, air and soil pollutants, the species yet to be described may have even further unknown or hidden implications (Coleman *et al.* 2004).

Brussaard, de Ruiter and Brown (2007) tried to put a world-wide annual economic benefit value on soil biodiversity. They suggested that greater than US $ 760 billion is the value of soil biota in recycling organic wastes, US $90 billion in nitrogen (N) fixation, US $121 billion in bio-remediation of polluted soils and water, US $160 billion in controlling pests, particularly in agricultural systems, and about US $200 billion in the pollination of plants by insects, that often spend a critical stage of their life–cycles within the soil. Brussaard, de Ruiter and Brown (2007) further claimed that soil biodiversity is important for resistance and resilience against environmental stress and disturbance and cited examples that showed that stability (ability to recover from a stress or disturbance) is dependant on agricultural management regimes and level of disturbance. Research by Garbeva, Voesenek and van Elsas (2004) found experimentally that the soil with the highest soil microbial diversity had the highest disease suppression.

The study of soil microbiological diversity is complex and in the past there has been limited scientific research into the effect by and on annual cropping. One of the reasons being that a majority of soil microbes (and often fauna as well) are usually dormant or inactive for varying time periods (Jenkinson and Ladd 1981). Sylvia *et al*. (2005) added that other reasons are that when environmental conditions and food sources are ideal for a particular microbe, their population can grow exponentially as long as those niche conditions continue and if their population numbers are not adversely affected by predation, competition for limited resources or through amensalism (production of growth-inhibiting substances by other populations). They further stated that the complexity of soil microbiology is further

exacerbated when populations of microbes grow and alter their environment influencing substrate levels which may favour the growth or decline of other microbial populations.

The co-evolution of plants and soil organisms has flourished in a complex relationship within the soil environment (Whalen 2004). Within the soil there is a range of diverse soil organisms that have evolved along with different plant types but the introduction of modern crop production that often uses only one plant species per crop has meant that there is a reduction in the diversity of plant species. The resulting effect is unknown on the numbers and complexity of soil organisms and their predators. These soil organisms include microscopic bacteria, fungi, protozoa, nematodes and micro-arthropods.

2.4.1 Soil biota and plant interactions

2.4.1.1 Ecological role of soil biota

Altieri (1999) in a review of the ecological role of biodiversity in agroecosystems reported that biodiversity (all species of plants, animals and micro-organisms existing and interacting within an ecosystem) performs many ecosystem services. These services not only include the economic benefits of production of food, fibre, fuel and income but also environmental benefits such as the recycling of nutrients, control of local microclimate, regulation of local hydrological processes, regulation of the abundance of undesirable organisms and detoxification of noxious chemicals. Abbott and Murphy (2007) stated that there has been a considerable decline in soil organic matter and associated loss of soil structure in many intensively cropped areas of the world and this, they claim, has caused both scientists and landowners to re-examine components of the farming system, so as to benefit from biological processes. Altieri (1999) claims that by reducing biodiversity, a simple and artificial ecosystem is created, that constantly requires human intervention to increase soil fertility and regulate pests. He believes that for farmers to achieve benefit from biological processes the key strategy is to restore functional biodiversity of the agricultural landscape so as counter the growing fears for the long-term sustainability of highly input-dependent and ecologically simplified food productions systems.

2.4.1.2 The rhizosphere

The activity of the soil biota is largely responsible for nutrient transformations in soils and underpins a number of fundamental soil properties such as fertility and structure (Pankhurst

et al. 1995). Plant roots play an integral part in the size and activity of soil biology with extraordinary interactions between them and soil organisms (Watt, Kirkegaard and Passioura 2006). The rhizosphere is the region of soil within millimetres of a plant root in which there is a vast range of complex biological and ecological processes at work (Bais *et al.* 2006) and a recognized hot spot for microbial and faunal activity (Beare *et al.* 1995). Cardon and Cage (2006) likened the rhizosphere to commodity exchanges, where organic C flux from roots fuels decomposers that, in turn, can make nutrients available to roots resulting in a complex interaction between plant roots, root exudates, micro-organisms and micro and meso-fauna which enhances nutrient turnover and plant growth.

Manning *et al.* (2008a) explored the concept that plants interact with soil biota through root exudates and litter inputs in the soil as well as having an environmental effect on soil structure and moisture. They found that plants can strongly influence several soil properties and this was strongly correlated with plant biomass. Research by Bunemann *et al*. (2008) into different management strategies in a 26 year trial found that while microbial biomass was the highest in treatments which had maximum organic matter content, the microbial community composition was primarily driven by plant type (crop rotation) and to a lesser degree by tillage.

Plant root exudates include the secretion of ions, free oxygen and water, enzymes, mucilage and a diverse array of C-containing primary and secondary metabolites (Bais *et al.* 2006). These exudates can stimulate microbes to produce exo-enzymes that degrade organic matter, promote N cycling as well as directly affecting the expression of genes in microbes that may control their function to the benefit of the plant (Paterson 2003). These exudates can create complex interactions with soil microbes, attracting some, repelling others or attracting both mutualists and pathogens (Bais *et al.* 2006). As well as supplying substrates to micro-organisms, roots modify the rhizosphere chemically and physically (Paterson 2003). Microbes can also influence plant growth directly by producing hormones or toxins that can either stimulate or impede root function and morphology (Sylvia *et al.* 2005).

2.4.1.3 Symbiotic associations

It is likely that plants and micro-organisms have co-evolved and it is in the rhizosphere where most of the mutually beneficial associations occur (Paterson 2003) but microbes can also live in, or on, host plants. Steinert, Hentschel and Hacker (2000) have suggested that it is bacteria, through intimate association with hosts, which are the drivers of evolutionary changes to new speciation and diversification.

Microbe and plant interactions can be symbiotic, pathogenic or commensal. Symbiosis is common between micro-organisms and plant hosts and results in a beneficial association to both. The most researched examples that are important in most cropping systems are between the bacteria *Rhizobium* and leguminous plants (Stacey, Burris and Evans 1992) providing N to plants. *Arbuscular mycorrhizal* (AM) fungi also form many symbiotic relationships with some plants. They not only provide nutrients to plants but help plants survive some biotic and/or abiotic stress such as those produced by plant pathogenic organisms (Maia, da Silveira and Cavalcante 2006). Important plant root pathogenic fungi that cause reduced crop yields include *Gaeumannomyces graminis* var. *tritici, Rhizoctonia solani* and *Pythium irregulare* (Pankhurst *et al.* 1995) but an increased diversity of micro-organisms in soils allows the proliferation of predators of pathogens (Govaerts *et al.* 2007) that can help to protect crops.

A starting point for restoration of soil where soil biology has declined is to understand, in detail the different components of the biota in the soil. Collectively soil biota form a food web of interdependent relationships and organisation and knowledge of this gives an understanding of "who-eats-who" that allows the transfer of food energy from plant source to other organisms (Krebs 2001). There are many organisms that are part of the soil food web that is the foundation of a healthy soil.

2.4.2 Algae and cyanobacteria

While lichens and mosses are dominant in wet soil environments, as the soil dries out, algae and cyanobacteria become more dominant. Both algae and cyanobacteria are capable of photosynthesis and are found almost anywhere where there is light and bare soil where together with bacteria and fungi help to form biological crusts on the soil surface. These biological or microbiotic crusts have been described by Eldridge and Greene (1994) as

having an important ecological role in Australian rangeland conditions especially in times of drought via providing soil cover and helping to increase infiltration. Reduced colonization of these organisms is caused by thick plant cover and if the soil pH is less than six. While they need moisture for metabolic activity, they can withstand long periods of desiccation (Sylvia *et al.* 2005). Research by Tomaselli and Giovannetti (1993) found that some strains of cyanobacteria survived one year of drought conditions which indicates the resilience of some species of microbes to disturbances.

2.4.2.1 Ecological role of algae and cyanobacteria

While the role of algae and cyanobacteria have been identified in Australian semi-arid rangeland environments as having an important role in forming microbiotic soil crusts (Eldridge and Greene, 1994) there has been little research of their importance in cropping soils. This could be due to their sensitivity to mechanical disturbance (Belhap and Eldridge, 2001). Belgium research by Knapen *et al*. (2007) has, however, found despite this sensitivity microbiotic crusts can have an important role in reducing soil loss in some cropping soils.

Sylvia *et al*. (2005) summarized the role of the photosynthetic algae and cyanobacteria as being the major contributors to the organic C pool in both desert and marine ecosystems. They also provide N to soils, as many fix atmospheric N, chelate nutrients, increase mineral weathering rates, influence local hydrologic cycles and help retain nutrient-rich dust. Cyanobacteria secrete copious amounts of mucilage which helps bind soil particles together, so can help reduce erosion in bare areas. They also form the base of the soil food chain, providing a food source for other soil biota (e.g. nematodes, protozoa and micro-arthropods) (Sylvia *et al.* 2005). Obana *et al.*(2007) investigated the effects of *Nostoc,* a terrestrial cyanobacterium, which is known as a pioneer organism that photosynthesizes as well as fixes atmospheric N and secretes polysaccharides containing C and N which soil micro-organisms can feed upon. They found that an inoculation of *Nostoc* increased the plant growth of *Brassica rapa* var. *peruviridis* and plant iron uptake and concluded that this organism might be a potential candidate for increasing soil organic matter and reclaiming degraded soil ecosystems.

2.4.3 Bacteria

Despite the overwhelming majority of soil bacteria not having been cultured, characterized or given a name, researchers are rapidly discovering that they are a vital component of soil health. Sylvia *et al*. (2005) describes bacteria as microscopic single celled organisms that are considered the most numerous of soil microbes especially in organic rich surface layers but their population size can vary with nutrient availability, temperature, aeration and other abiotic and biotic factors.

2.4.3.1 Ecological role of bacteria

Sylvia *et al.*(2005) described how the primary niche in soils for bacteria is to function as decomposers as they can rapidly metabolize the sugars, starches, fats and proteins in soil organic matter. The other substances such as lignin, wax, oil and resin in plant residue are more slowly decomposed by bacteria and these materials, along with polyaromatic compounds, become part of the humus organic fraction in soils. Actinomycetes can break down an enormous variety of organic compounds that other soil microbes cannot. These include chitin, lignin, hemicelluloses, keratin, and other plant, fungal and animal polymers. Besides decomposing organic matter, other species of bacteria play an major part in N cycles by converting N gas to ammonium, converting ammonium to nitrites and nitrates as well as converting these back to N gases (either as N_2 or N_2O). Other species have a similar role in the sulphur cycle either reducing sulphates to H_2S or by oxidising sulphur to sulphates. A bacterium also produces organic or inorganic acid by-products from their metabolism which release soluble materials such as phosphates and metal ions into the soil solution. These include iron, manganese, mercury, and selenium.

Bacterial diversity may also aid in disease suppression. Deacon (2006) claims that one of the major crop fungal root disease, take-all, has been found to be controlled by the presence of a small subset of bacterial fluorescent pseudomonads by a process called quorum sensing. This control mechanism is caused by a continual release of N-acyl homoserine lactone molecules by the fungus and when the concentration of these molecules reach a certain level antibiotic producing genes in the gram-negative bacteria are switched on which reduces the take-all disease (Deacon 2006).

Bacteria survive in soils by adhering to soil particles, plant roots or other soil organisms. Gram positive *Bacillus* and *Clostridium* species form endospores in response to nutrient depletion or other environmental stresses and are extremely resistant to heat and other harmful agents such as radiation and toxic chemicals which enhance survival under adverse conditions (Sylvia *et al.* 2005).

2.4.4 Fungi

In terms of biomass, fungi are the most abundant group of micro-organisms in the soil accumulating between 500 and 5000 kg of wet biomass per hectare (Metting 1993). They have a filamentous body that releases enzymes which break down complex molecules to simpler forms and then the body absorbs these materials as a source of food (Sylvia *et al.* 2005). Arbuscular mycorrhizal (AM) fungi could be the most abundant fungi in agricultural soils (Olsson *et al.* 1999) and they are obligate and symbiotic with plants providing phosphorus and zinc to plants in return for C-based substrates (Sylvia *et al.* 2005).

2.4.4.1 Ecological role of fungi

Along with bacteria, fungi are basic decomposers of organic matter and other soil biota feed upon them. In the soil environment, they are important as food sources, pathogens, beneficial symbionts, saprophytes to degrade crop residues, and biotic agents to improve soil structure and aeration (Sylvia *et al.* 2005). Williamson and Wardle (2007) commented that fungi tends to dominate the microbial biomass in the non-rhizosphere and some fungi can extract and subsequently translocates nutrients from the mineral horizon to the surface organic matter and even into the overlying litter layer creating an important mechanism for nutrient redistributions in soil ecosystems.

Some species of fungi produce enzymes that solubilise nutrients so making them available for plant use. Whitelaw, Harden and Bender (1997) found that an isolate of the fungus, *Penicillium radicum,* inoculated onto wheat roots increased availability of phosphorus, plant uptake and yield, both in glasshouse and field trials.

Certain species of fungi act as natural population regulators helping, for example to keep insect and nematode pests in check (Deacon 2006). While many species of bacteria and actinomycetes can cause plant diseases, Brussaard, de Ruiter and Brown (2007) claim that it is fungi that do the most damage through soil-borne diseases such as wilts, root diseases

and blights. Some fungal species however are antagonistic to other fungi and can reduce the incidence of fungal disease. *Trichoderma* species can produce antibiotics antagonistic to *Pythium* and *Rhizoctonia* as well as chitinase and β-1, 3-glucanase (which break down fungal cell walls) and can physically coil themselves round the hyphae of other fungi (Deacon 2006).

Soil fungi also have a role in improving soil structure. Tisdall (1991) showed that fungi hyphae exude a mucilage of polysaccharides that along with other temporary binding agents (roots and root hairs) help bind micro-aggregates (0.02-0.25 mm diameter) into stable macro-aggregates (>0.25 mm diameter). Ritz and Young (2004) claim that as well as adhesive mechanisms fungi can also improve soil structure via charge and enmeshment mechanisms. They further claim that fungi can however destroy soil structure via decomposition of organic matter that affects soil aggregation.

2.4.5 Protozoa

Soil protozoa are mostly single celled organisms, smaller than their aquatic counterparts, are non-photosynthetic and are most active and abundant in wet soil (Singer and Munns 1996).

Foissner (1999) claimed that protozoa are an essential part of the soil ecosystem, responsible for about 70 % of soil animal respiration and an important part of the soil food web. They are also an important element in energy flows from the bacteria they consume to animals that consume them. Experiments conducted by Bonkowski and Schaefer (1997) provided evidence that earthworms (*A. caliginosa* in particular) actively search for places with high protozoan densities and that they may play a significant role in earthworm nutrition. Active forms may also be digested by arthropods serving protozoa as a transformer of bacterial protoplasm into higher trophic levels (Bamforth 1988).

Protozoa also enhances nutrient cycles and may be responsible for about 14-66% of C and 20-40% of N mineralisation (Foissner 1999). This is achieved by the grazing of bacteria by protozoa. Bacteria mineralise N for their own use but they need to be grazed to make that plant biomass N available for plant uptake (Clarholm 1985). The excess nutrients that the grazers gain from bacteria that are not required for their own use are secreted into the soil in plant available form. Griffiths (1989) found that nitrification in a clay loam soil was

significantly enhanced by increasing protozoan numbers either by the addition of supplementary nutrients or increasing numbers of bacteria. Kuikman *et al*. (1990) found that inoculation of soil with protozoa increases plant growth and acquisition of N.

Bamforth (1995) asserted that protozoa have important survival mechanisms such as ability to enter tiny spore spaces as well as undergoing encystment, allowing them to withdraw from environmental stresses (under dry conditions this is achieved by the process of hydrobiosis) with minimal mortality and to excyst quickly in response to favourable conditions and to increasing bacterial populations. This allows protozoa to quickly increase the amount of soluble plant nutrients as well as decreasing the competitive abilities of bacteria.

The main soil protozoa are naked amoebae (over 60 species recorded) which are less than 30 µm and attach themselves to soil particles feeding mainly on bacteria and some fungi. They may help reduce inoculums of plant pathogenic soil fungi (Foissner 1999). Experiments by Clarholm (1985) showed that soil samples with naked amoebae that fed on bacteria released more N to plants than soil samples that were just inoculated with bacteria. These results demonstrated that soil bacteria can mineralize N from the soil organic matter to support their own growth but it is the grazing of the bacteria that makes bacterial biomass N available for plant uptake. Clarholm (2005) also made the observation that there are more naked amoebae in non-planted microcosms receiving repeated small N and C additions but in the presence of plants, the number of amoebae does not increase following N and C additions. She also noted that the plants in soils receiving N additions, but without protozoa did not grow as well as the plants with the same N additions plus protozoa. This indicates the complex interactions between soil, microbes and plants.

Other important soil protozoa are testate amoebae which have a shell. There are over 300 terrestrial species and may be the most abundant protozoan (Foissner 1999). Flagellates are another group of protozoa with about 260 species in soils. They are abundant, small (less than 20 µm), with a generation time of about 5 hours and feed mostly on bacteria. Ciliates, the final group of protozoa, number about 300 species have a high diversity in soils occurring mainly in the litter layer but there are fewer numbers in arable lands (Sylvia *et al.*

2005). While a soil might function with a few protozoan species, high diversity allows systems to respond to changing seasons and climate (Bamforth 1995).

2.4.6 Nematodes

Nematodes are a multi-cellular eukaryote, unsegmented and usually microscopic roundworms (Sylvia *et al.* 2005). The four broad groups of free-living nematodes are bacterial and fungal feeders, predatory nematodes and omnivores (who eat a variety of organisms) (Ingham 2000). Another group are the root-feeders that are plant parasites which can be ecto-parasitic (free-living outside their hosts) or endo-parasitic (living within their hosts) or they can just be free-living in their infectious, larval stage (Sylvia *et al.* 2005). Most nematodes prefer to be in that part of the soil habitat that provides inter-aggregate pore spaces and fresh organic matter (Blanca *et al.* 2006).

2.4.6.1 Ecological role of nematodes

Nematodes are thought to enhance soil quality by regulating the populations of other soil organisms; mineralizing nutrients into plant-available forms; providing a food source for other soil organisms that influence soil structure and consuming disease-causing organisms (Ingham 2000). Bird and Ryder (1993) researched the role that microbe-consuming nematodes have on pathogens such as *Rhizoctonia solani*, *Pythium* spp. and *Gaeumannomyces graminis* (take-all). Individual genus such as *Cephalobus* sp., the most abundant of the soil bacterial feeders, can have a large impact on control of microbial biomass and thus the availability of nutrients to plants (Yeates 2003). While individual species of nematodes are important it has been shown that increased diversity of soil nematodes can increase nutrient turnover and plant growth (Ingham *et al.* 1985).

It has been demonstrated by laboratory and field experiments that those nematodes that feed on bacteria and fungi have nutrient excretions that are in plant available form (Bardgett *et al.* 1999). One important soil nutrient released by microbial feeding nematodes is inorganic N. Research by Tu, Koenning and Hu (2003) demonstrated that root-parasitic nematodes can also enhance N mineralisation in the form of nitrates. They claim this was caused from the leakage of damaged plant root cells providing active sources of energy and nutrients for soil microbes and the higher C availability and microbial activity stimulated net N mineralisation. Root-parasitic nematodes of the genus *Pratylenchus* are

however deleterious to agricultural production and are probably the major parasite of cereals in Australia (Hodda *et al.* 1999). They may be controlled by other soil biota that graze upon them (Yeates and Wardle 1996) as well as nematode-parasitic fungi (Sylvia *et al.* 2005) which may keep parasitic nematode populations in check in a balanced food web ecosystem.

2.4.7 Other soil organisms

This project is focusing on the microbial populations because of their importance in decomposition, nutrient cycling, retention and availability to plants as well as disease suppression and improving soil structure. It is important however to acknowledge that there are other groups of soil fauna higher in the food chain that also have roles to play in decomposition of organic matter, cycling of nutrients and improving soil structure. These include microarthropods (collembola and mites), macroarthropods (larger insects, spiders, myriapods, millipedes, centipedes, scorpions, ants, termites, flies and beetles) and Oligochaeta (earthworms).

2.4.8 Soil biota interactions

Soil biodiversity is influenced by abiotic factors such as climate, geography and soil or sediment type (Coleman 2008). It may also be influenced by population interactions (predator-prey, and extensive omnivory). These interactions have a marked impact on nutrient cycling in soils, enhancing N and phosphorus mineralization and subsequent plant nutrient uptake (Ingham *et al.* 1985). Predatory – prey interaction can be a positive for prey, for example, if there is an over-compensatory response by the prey after a decline in predator numbers. This was seen to occur when fungus was subjected to grazing by collembola resulting in increased hyphal length (Coleman 2008). Coleman (2008) also stated that experimental evidence is supporting the concept that increasing species richness increases stability of ecosystem properties. If farmers are to adjust to ecosystem changes caused by either their land management techniques or by climate change then they may need to have resilient agroecosystems through the maintenance of high biodiversity of soil biota.

2.5 AUSTRALIAN FARMING SYSTEMS

Many farmers have adopted no-till agriculture in the hope that it is a more sustainable farming system that encourages soil biology giving greater soil health. The change to no-till often resulted from research which demonstrated that cultivation was causing environmental damage such as soil degradation (Holland 2004). Research was suggesting that no-till appeared to improve some soil physical and chemical properties (Balesdent *et al.* 1990; Cambardella and Elliot 1992; Dalal 1989; Dalal, Henderson and Glasby 1991; Havlin *et al.* 1990; Linn and Doran 1984). It also appeared that no-till increased microbial biomass (Gupta *et al.* 1994) and that less soil disturbance was advantageous for fungal hyphae establishment (Holland and Coleman 1987).

In Australia, the potential of conservation tillage to reduce erosion was well researched and demonstrated to Australian farmers during the 1960's and 1970's (Pratley and Rowell 1987) and the practice became possible in Australia when knockdown herbicides were introduced (Southorn *et al.* 2004). There were agronomic problems before no-till was widely accepted (Lawrie *et al.* 2000) such as weed control, nutrient tie-up and lower crop yields but by the end of the 1990's some of these problems had been addressed and in 2004 an estimated 72% of Australian farms had at least used direct drill methods to sow some of their crops (Hodges and Goesch 2006). Despite this high percentage there has been an uneven adoption of no-till across Australia with Western Australia's adoption rate being as high as 80% (Crabtree 2006) and as little as 24% in northern New South Wales (Scott and Farquahason 2006). This could be the result of no-till substantially reducing wind erosion in the sandy soils of Western Australia which is less of a problem in New South Wales. In NSW the regional adoption is variable. Young and Schwenke (2006) suggest that at least 80% of north west NSW is under some form of reduced tillage with the greatest adoption on Vertosols (fine textured cracking clays) compared to an estimated 13% adoption of direct drill in other parts of NSW (Connell and Hooper 2002).

2.6 BENEFITS OF N0-TILL

There have been many recorded benefits of stopping, or at least reducing soil cultivation. In Australia these include a significant decline in erosion (Southorn *et al.* 2004) and reduced run-off (Packer, Hamilton and Koen 1992) resulting in improved efficiency of water capture

and its subsequent use by crops increasing productivity, especially in areas that have lower in crop rainfall (Felton, Marcellos and Martin 1995; Radford *et al.* 1995).

Experiments by Radford *et al*. (1995) showed that no-till can result in more stored water in the fallow period than cultivated soil. They contributed the benefit not just to the retention of maximum levels of soil-protecting surface stubble but, to the greater volume and density of large macro-pores, delaying time to ponding and commencement of run-off. Studies into farmers' gross margins in northern New South Wales, where crops are grown mostly on stored water, have shown techniques that involve a combination of no-tillage, stubble retention and controlled traffic, have better gross margins than others that do not use this technology (Rummery and Coleman 2000).

World wide there have been many long-term studies into the benefits and sustainability of no-till. After 44 years of research in Ohio, USA Mestelan *et al.* (2006) have shown that no-till is not just sustainable and increased yields, but it can also enhance soil quality. Six, Elliot and Paustian (2000) proposed that C sequestration is increased in no-tillage systems and Denef *et al.* (2004) found that in long-term no-till systems, soil C levels were higher than in ploughed treatments. Lal (2004) proposed that no-till was one weapon to help fight climate change and to help with world food security. In Canada, conservation tillage was found to help increase protective surface residues, reduce soil erosion, maintain long-term soil productivity and reduce sediment and phosphorus loadings into watercourses (Stonehouse 1997). Continuous no-till cropping and crop-pasture rotation using no-till systems were shown to maintain, or even promote sustainability in Uruguayan soils (Ernst 2006). A 12 year study in China of no-tillage regimes with full residue cover showed that they raised the water use efficiency by 18.6% as run off was reduced. Wheat yields were also increased with a reduction of operation costs (Gao, Kulig and Jing 2004).

While these have all been positive aspects of no-till, some researchers have recorded negative aspects of conservation agricultural practices. Watt, Kirkegaard and Passioura 2006) have stated that despite the major improvements in soil properties from conversion to conservation farming, better crop yields do not necessarily follow. They theorized that the range of possible contributory factors includes: increased pests and diseases; allelopathic effects from retained stubble; greater residual effects of herbicides; growth-

inhibitory bacteria in the rhizosphere; slower root growth in the harder unploughed seed bed; inhibitory signals passing from roots to leaves when the roots are experiencing less than ideal soil conditions; and concentration of nutrients in the surface soil.

There have been some reports that reduced till and no-till has increased emissions of the greenhouse gas N_2O (Changsheng, Frolking and Butterbach-Bahl 2005; Doran 1980b). A review by Dalal *et al.* (2003) also found that N_2O emissions were higher under no-till and trash retention in eastern Australia. By studying the results of 25 studies of field emissions of N_2O, Rochette (2008) found that generally no-till increased N_2O emissions in poorly-aerated soils but was neutral in soils with good and medium aeration. They asserted that the increase in soil C may actually create a negative greenhouse balance for many poorly-drained fine-textured agricultural soils in humid climates.

Packer *et al.*(1998) found no significant improvement in infiltration rate, organic C content, or soil bulk density after comparing three years of direct drilling compared with conventional tillage. Chan, Heenan and So (2003) observed that soil organic C levels only significantly increased in soils in higher rainfall areas (greater than 500 mm per year) that are direct drilled compared to conventionally cultivated. The two key features of these research projects were the lack of stubble retention and their short duration.

In longer-term studies in no-till systems some researchers have found benefits that have not been apparent in short-term direct drill studies. So, Grabski and Desborough (2004) found that in a 14 year comparison of no-till near Grafton with conventional farming there was an improvement in soil organic matter levels, more stable aggregates, higher porosity, higher number of macro-pores and more moisture infiltration. The result was less run-off and soil loss in the no-till system. They also noted that, despite an initial depression of crop yields in a no-till system, eventually the no-till system did achieve higher yields because of these improvements in soil health. Sayre *et al.*(2006) completed a 15 year research project into the profitability of traditional cultivation compared with no-till with and without stubble retention in Mexico. They found that the most profitable and sustainable system was no-till with retained stubble. The worst profitable system was also a no-till system but when the stubbles were bailed and sold for hay.

Southorn *et al.*(2004) proposed that direct drilling by itself will not improve soil physical quality but will help in a system that also maximises plant biomass, retains stubble and removes compaction stresses such as using control traffic technology to reduce the area of wheel tracks. It was estimated that about 10% of the farms in the Australian grains industry had adopted control traffic to plant crops by 2006 (Yule, Neale and Chapman 2006). Many of these farmers were adopting 2 cm GPS tractor guidance to reduce the effect of wheel compaction and to allow inter-row planting (Tullberg and Bromet 2006).

2.7 EFFECT OF FARMING PRACTICES ON SOIL BIOLOGY

Despite limited research into the benefit of soil biota (apart from macro fauna) to cropping systems (Bell *et al.* 2006) there has been some research investigating the influences of tillage, fertilizer and herbicide use on different parts of the food web.

2.7.1 Reduced tillage

Effects of reduced tillage on soil biota are not clear-cut with variable results being reported. Mechanical disturbances such as tillage has been found to reduce algae and cyanobacteria populations (Belnap and Eldridge 2001), predatory bacteria-feeding soil protozoa (Pankhurst *et al.* 1995), nematodes (Hodda *et al.* 1999) and micro-arthropods, especially combined with stubble removal (Pankhurst *et al.* 1995). Field trial research by Gupta *et al.* (1994) suggested that excessive tillage and stubble burning have a negative impact on microbial biomass and microbial activity in cropping soils near Harden, New South Wales. Pankhurst *et al.* (1995) found that populations of bacteria tended to be higher in cultivated soil than in no-till soil, whilst fungal populations generally tended to be higher in no-till soil at 0-5 cm depth. A study by Bell *et al.* (2006) indicated that just reducing tillage may not significantly improve biological activity. They investigated the biological activity in cropping soils of northern Australia which indicated that zero tillage and stubble retention was only producing relatively small benefits.

Daniels, Brown and Deegan (1994) claimed that tillage reduces earthworms because, quite simply, it chops them into pieces and that a single pass with narrow sowing points does not destroy as many. Research by Doube, Buckerfield and Kirkegaard (1994) found though that cultivation in itself was not the sole cause of declining earthworm populations but it also depended on the availability of suitable earthworm food in the soil, especially at the soil

surface. The removal of stubble by burning has been shown to reduce earthworm numbers; soil respiration rate and soil fungal mass (Heenan 2002).

Radford *et al.*(1995) found that reducing tillage and hence decreasing soil disturbance as well as retaining crop residues on the soil surface results in a soil micro-environment favourable to macro-fauna survival. Pangnakorn *et al.* (2004) found that in south east Queensland there was a significant increase in the beneficial soil insects (Collembola and Acarina) in a controlled traffic and zero tilled treatment over other treatments without control traffic.

Wardle (1995) found that tillage could strongly elevate or reduce macro-faunal group diversity with little affect on micro-fauna. The magnitude of these effects depends on soil type, climate and tillage operation. Bardgett *et al.* (2005) claims disturbance due to agriculture can reduce the diversity of the soil microbial and faunal communities. These include reductions in nematodes, earthworms, termites and organisms that are involved in direct interactions with plants such as AM fungi.

The lack of tillage has in some cases increased soil biological constraints such as increasing inhibitory micro-organisms and phyto-toxins that have been noted to decrease crop growth in harder-setting direct drilled soils of southern Australia (Watt, Kirkegaard and Passioura 2006). Simpfendorfer *et al.*(2001) found that direct drilled soils that have intact bio-pores may also have high concentrations of deleterious micro-organisms (such as *Pseudomonas* sp.) remaining from roots of previous plants and these may produce root inhibitory enzymes that reduce the early growth of some crops. Govaerts *et al.* (2007) found that in Mexico, although zero tillage increased incidence of root rot and parasitic nematodes this did not affect yield as much as other critical plant growth factors such as infiltration and water availability which were greatly improved by zero tillage. The improved benefits of infiltration and water availability that they found in zero tillage systems were more beneficial to yields, overcoming the negative shortcomings of increased incidence of disease.

2.7.2 Pesticide (herbicide, fungicide, insecticide and nematicide) use

One of the main features on Australian no-till system is the strong reliance of herbicides to kill competing weeds. There has been limited research into the influences of pesticides and

herbicides in particular, on the soil food web. Some authors make specific statements such as N fixation by *Nostoc* can be decreased by exposure to insecticides, herbicides and phenolic compounds (Sylvia *et al.* 2005). Research by Mishra and Pandey (1989) found in their laboratory research on herbicides applied to field rice that 2, 4 dichlorophenoxyacetic acid (2, 4-D) (a chemical that is also used in dry-land cropping) can actually stimulate the growth of *Nostoc* and increase N fixation and uptake of nitrate but not ammonium N. They did find that high doses did inhibit the uptake of both nutrients. They discovered that some soil properties such as higher pH, presence of organic C and some amino acids gave protection against toxicity of some herbicides.

Eisenhauer *et al.* (2009) stated that many pesticides including herbicides are degraded by soil bacteria so they might actually increase soil microbial activity. They did find experimentally that the organophosphate insecticide chlorpyrifos and organophosphate nematicide fosthiazate increased certain soil microbial parameters but dimethoate, an organophosphate insecticide and acaricide, decreased them. Rattanakreetakul, Korpraditskul and Chamsawarng *et al.* (1990) demonstrated by using anaerobic plate experiments that paraquat herbicides can inhibit the growth of many soil bacteria. Pratt *et al* (1997) argued however that experiments of this type provide little information about community structural changes within the actual soil both in the short and longer term.

A review by Bunemann *et al.* (2006) found some pesticides and fertilizers (possibly with toxicity of metal contaminants) had been shown to have detrimental effects on some soil biota but the main adverse effects were from copper toxicity from fungicides and management that resulted in soil acidification e.g. the leaching of nitrates through the soil profile. They concluded that pesticides have little long term influence on soil biota and that any practice that increases levels of soil organic matter also increases soil biological activity.

Van der Werff (1996) suggested that any negative influences of pesticides depended on the type and specificity of the chemical, the rate of application and the susceptibility of target species. A review by Murphy *et al* (2007) claimed fungicides, nematicides and soil fumigants may have significant temporary negative effects on SMB C and herbicides and insecticides tend to have smaller and more variable effects. They also believe that modern pesticide formulations that have increasing specificity and reduced doses of active ingredients

reduces the recorded negative effects of pesticides on soil micro-organisms. Abbott and Murphy (2007) suggested that those pesticides that may kill some beneficial soil fauna could alter the food web and, depending on the type of shift, it may also alter the nutrient supply for plants.

2.7.3 Fertilizers

With the advent of modern farming methods many inorganic fertilizers have replaced C-based fertilizers such as manure. High levels of some inorganic fertilizers have the ability to cause osmotic stress to microbes (Yevdokimov *et al.* 2008). High P-fertilization has been implemented in low AM fungal formation in some soils (Ryan and Graham 2002). Research by Pankhurst *et al.*(1995) found that N fertilization at 80 kg/ha at sowing reduced mycorrhizal fungal infections, protozoa levels and total counts of micro-arthropods. Bell *et al.* (2006) found that there were minimal effects of inorganic N or P fertilization on soil biota except on the *Dorylaimida* free-living nematode community.

2.7.4 Other management practices

Other management practices commonly used in the no-till system may be detrimental to certain parts of the soil food web. Bell *et al.*(2006) concluded from their research on Vertosol soil in the northern wheat belt of Australia that the practice of long fallowing to recharge soil moisture levels and the reduction of pasture phases in cropping country significantly lowered soil biological parameters that they measured. This effect was modified by a short duration green or brown manure crop. Ryan and Graham (2002) listed practices such as soil fumigation, use of non-responsive plant varieties or rotations based primarily on non-mycorrhizal crops that may limit AM fungal colonisation. The use of some brassica “break crops” such as canola has been demonstrated to successfully control the negative yield effects of some non-desirable soil organisms (Smith, Kirkegaard and Howe 2004) but it has also been shown to have a negative effect on the beneficial arbuscular mycorrhizal fungi populations (Owen *et al*. 2010).

Despite no-till farming producing many desirable outcomes for Australian farmers, the addition of organic and non-organic amendments may be beneficial to no-till agriculture (especially if there has been a low volume of retained crop residues) in restoring some parts of the food web that might be disadvantaged by certain management practices. Their

addition may possibly help restore soil C levels and help farmers to better adjust to the negative effects of possible climate change. The following section examines in detail, the impact on soil properties with the addition of organic amendments.

2.8 ORGANIC AMENDMENTS

Agricultural soils that have been depleted of soil organic matter due to past practices may benefit from the application of organic amendments. There has been much research showing that incorporation of organic amendments can significantly alter physical, chemical and biological properties of a soil ecosystem (Bandick and Dick 1999; MacRae and Mehuys 1985; Ndiaye *et al.* 2000; Schutter and Dick 2001). There has been other research to show that surface applications, without incorporation of organic amendments in a no-till situation can also be of benefit (Lal and Stewart 1995).

Salamon *et al.*(2006) researched the influences of organic amendments (wheat bran, pet food and beech wood) on the soil food web and they found that microbial biomass was moderately increased by their additions. In particular Lumbricids, nematodes, collembolans, gamasid mite and staphylinid populations were also increased but oribatids, prostigmatids and lithobiids decreased. The numbers of enchytraeids, millipedes, uropodine mites, pseudoscorpions and spiders remained unaffected probably indicating that parts of the soil food web were resilient, responding little to changes in resource supply.

Research has also been conducted into effectiveness of organic amendments in disease suppression. There has been a general observation that organic amendments which are able to provide an energy source for soil micro-organisms reduces general pathogen numbers although it can take time (Bailey and Lazarovits 2003). There is still a need to further study the complex process of organic-mediated disease suppression but Ochiai *et al.* (2008) found that *Verticillium* wilt disease suppression was positively correlated with a number of general soil microbiological properties, and suggested that general microbial suppression was the dominant mechanism controlling this disease with the addition of organic amendments. Rotenberg *et al.* (2007) found that root rot in a vegetable crop rotation was suppressed by adding, in spring, various amendments of paper mill residues alone or composted with or without bark.

In a review of organic amendments, Vetterlein and Hutti (1999) highlighted their possible risks. These include nutrient imbalance; not matching nutrient release with plant nutrient demand, such as leached N in high N sources or N immobilization in low N sources of organic amendments; heavy metal contamination and existence of possible organic pollutants.

Taking the above possible risks into account some organic amendments that farmers can relatively easily source include crop residues or mulches, animal manures and compost.

2.8.1 Mulch

As a successful South American no-till farmer, Lamarca (1996) realised the benefit that retained surface residues have on cropping soil and on crop production. Many researchers have investigated the benefits of mulches and crop residues that are spread and left on the soil surface between successive crops and found that they contribute to the conservation of soil and water (Becher 2005; Lal and Stewart 1995; Pabin *et al.* 2004; Pabin *et al.* 2006) and in particular soil biological properties (Lal 1974; Potthoff, Joergensen and Wolters 2001; Saffigna *et al.* 1989; Tian, Brussaard and Kang 1993; Tu, Ristaino and Hu 2005; Walsh and Ragupathy 2007). Mulching has been observed to avoid yield reduction that is common in some European reduced tillage cropping systems (Glab and Kulig 2008) and has been shown to contribute to yield increase when soil temperature and/or moisture levels are improved by increased mulch levels (Lal 1974). Derpsch (2008) has argued that a thick layer of permanent mulch of at least 6, and if possible 10 tonne per ha of dry matter was the key for no-till success in South America. The thick layers act as good weed suppression, positively affecting soil moisture and temperature as well as improving chemical, physical and biological soil properties.

Delaying decomposition of crop residues is one way of maintaining a mulch layer. Australian researchers Summerell and Burgess (1989) found that when using dry weight as an indication of decomposition, the rate of surface stubble decomposition decreased at low water potentials and increased at higher temperatures. It was also found that burying the residues increased their decomposition. Retaining stubbles on the surface should therefore retard decomposition especially over dry summer periods.

Another way of increasing a mulch layer is to grow a cover crop and roll it down before it sets seed which leaves the unharvested residues still anchored to the soil but lying on the surface. Research by Wang *et al.* (2008) compared growing a cover crop that was incorporated and that which was left on the surface as a mulch. They found that when a cover crop of sun-hemp was incorporated it failed to enhance beneficial free-living nematodes but when mulched on the surface, there was a reduction of root-knot nematodes, enhancement of the bacterial-feeding nematode population densities, suppression of broadleaf weeds as well as increasing the following crops nutrient content and yield. They suggested that mulch has many advantages over incorporating cover crops. These include the slower release of nutrients, weed suppression, slower release of nematostatic compounds and as well as enhancing free-living nematodes that are involved in nutrient cycling and there might be a slowing of greenhouse gas emission. Blanchart *et al.* (2006) found that the use of legume cover crops (intercropped with maize) in southern Benin, West Africa significantly increased bacteria and predatory nematodes while reducing phytophagus types. Macro-fauna (termite, earthworm, millipede and centipede) populations were also increased. Price and Castor (2007) found that growing millet as a short-term cover crop terminated by herbicides in the northern grains region of Australia reduced erosion, increased ground cover and water infiltration, improved soil biological activity and in some cases increased winter crop yields, even though there was a slight increase in root-lesion nematodes.

There have been some studies on the rates of mulch required to have positive influences on soil properties. A Canadian study by Rees *et al.* (2002) showed that a rate of mulch as low as 2.25 Mg/ha reduced nutrient losses of nitrates and available P, K, Ca and Mg. An eleven year American study by Mulumba and Lal (2008) into the effects of mulch applications at 0,2,4,8 and 16 Mg/ha/year without plants being grown found that mulch rates had significantly effects on available water capacity, total porosity and soil moisture. The study determined that for increased porosity the optimum rate was 4 Mg/ha and for enhanced available water capacity, moisture retention and aggregate stability 8 Mg/ha was the optimum rate.

The effect of leaving the stubble standing or mechanically mulching was investigated by Mele and Carter (1999). In their experiment they found that mulching crop residues on the

surface and direct drilling wheat resulted in the highest earthworm density and biomass. Nelson and Mele (2006) found in their research that the type of crop residues influenced microbial diversity in the rhizosphere of wheat crops.

2.8.2 Manure

Manure is a source of an organic amendment that farmers may be able to source for their farms and which may have a positive effect on soil biota levels**.** Harinikumar and Bagyaraj (1989) found that farmyard manure, compared to conventional fertilizer, applied at 7.5 t/ha increased the number of AM fungal propagules. Manure applications have resulted in increased Collembola populations and increased abundance and biomass of earthworms in cropped soils (Altieri 1999).

Manures may also help in disease suppression. A review by Bailey and Lazarovits (2003) showed evidence that in low soil pH levels with the addition of manures with the presence of volatile fatty acids (VFA) which include acetic, propionic, butryric, isobutyric and valeric acid caused the death of the *Verticillium dahliae* microsclerotia pathogen. Some types of manure were also shown to increase the beneficial *Trichoderma* species to help reduce disease severity.

A risk of surface applying manure to fields is the loss of N as either ammonium or dinitrogen gases (escaping into the atmosphere adding to greenhouse gas emissions), and nitrates (leaching below the cropping zone possibly polluting groundwater). A Canadian study by Mkhabela *et al.*(2008) aimed to investigate this further. They applied 44 t/ha of manure in 2003 and 50 t/ha in 2004 and on the surface on the no-till trial in a 2 year silage corn crop. In 2004 110 kg N/ha in the form of diammonium phosphate (DAP) was supplied at planting while the plots received 140kg N/ha in 2005. At another site 25 t/ha of liquid dairy manure was left on the surface in 2004 planted to soybeans and 65 t/ha in 2005 planted to barley with no applications of inorganic fertilizer. At both sites, there were comparison trials that incorporated the manures. They found that NH_3 emissions were higher when manure was left on the surface rather than being incorporated. Soil nitrate levels generally were significantly higher when manure was incorporated at all depths of the profile. The risk is leaching the nitrates polluting groundwater. This study indicated that by not incorporating the manure nitrate leaching was reduced to groundwater. The possible reasons for this is

higher denitrification rates when manure is left on the surface, more NH_3 losses through volatisation reducing the N pool available for nitrification or greater N mineralisation when the manure was incorporated due to increased crop residue degradation by soil microbes. Besides nitrate leaching, when manures are applied in large amounts they may also run the risk of phosphate run-off contaminating surface water resulting in eutrophication. As well, there may be excessive levels of toxic material such as heavy metals and xenobiotics (resistant to biological breakdown) pathogenic viruses, bacteria and protozoa (Sylvia *et al.* 2005).

2.8.3 Compost

The possible pollution of groundwater by improper disposal of manures and waste streams to landfills could be overcome by composting (Reider, Janke and Moyer 1991). Composting has been defined as "a biological process in which biological wastes are stabilized and converted into a product to be used as a soil conditioner and organic fertilizer" (Douds Jr *et al.* 1997). One goal of composting is to sanitise the organic amendments so that no pathogenic or deleterious organism or weed seed (Sylvia *et al.* 2005) enters the cropping area. Many question the value of composting as a fertilizer given its relatively low N, P and K levels compared to commercial fertilizers but many practicing advocates of compost believe that it is a source of food for beneficial microbes that promote nutrient cycling as well as a medium to add beneficial microbes back into soil that may be depleted in them (Beck 1995).

There are often conflicting results using compost perhaps due to the variable quality which depends on the quality of its original sources and their age. Research by Abdelaziz *et al.*(2007) demonstrated that applying 35 t/ha compost in the bottom of rows of planted rosemary significantly improved plant oil and dry weight yields compared to recommended rates of NPK fertilizer but only when the compost was enhanced by adding *Azotobacter chroococcum* (a N fixing bacteria) and *Bacillus megaterium* (a phosphate-solubilising bacteria) to the compost. The compost and micro-organisms added separately actually reduced yield compared to the NPK fertilizer application. This highlights the complexity of the benefits of applying soil biology to achieve higher crop production.

American research by Carpenter-Boggs, Kennedy and Reganold (2000) found that the addition of composts (dairy manure mixed with pine shavings) significantly increased among other things, SMB C, respiration, and earthworm activity. The compost in these trials was incorporated by roto-tilling. There has been limited research of surface applied compost. Chan, Dorahy and Taylor (2007) investigated surface applying varying rates of compost on radish growth in pot experiments and concluded that there is an inconsistency in compost quality which produces highly variable plant responses.

Noble and Coventry (2005) reported that composts have consistently been shown to suppress many soil borne diseases such as damping-off, root rots and wilts. They claimed that although the process involved can be chemical and physical, it is mainly biological. A conference presentation by Hoitink, Stone and Han (1996) described how mature and stabilised compost can help with disease suppression. The mechanisms involved were described as competition, antibiosis, hyper-parasitism and the induction of systemic acquired resistance in the host. Bailey and Lazarovits (2003) cited examples where application of compost in field conditions help control diseases caused by *Sclerotinia minor, Pythium and Rhizoctonia*. They found that the problem with compost was the variability of the product and that this was the major limitation in recommending compost for disease control.

Composts that have high concentrations of VFA's can have inhibitory effects on disease pathogens and some composts may be effective as fungicides for controlling a broad spectrum of fungal diseases but more research is needed to clarify the interactions (Bailey and Lazarovits 2003).

The effect on root colonisation by AM fungi by addition of compost has been lightly investigated. Douds Jr *et al.*(1997) researched the effects of adding different composts on AM fungal root colonization on agricultural crops of corn, spinach and/or bell pepper and small grain rotation. The rate was determined to supply the same available N to each particular crop (356 kg compost N with N ranging from 1.6% N to 4.2% N dry weight). They found that high levels of chicken broiler and leaf compost had a significant increase in root colonization of AM fungi on maize roots compared to applications of raw dairy manure and recommended rates of fertilizer. This was not the case though for oats and capsicum

pepper. Other results have shown that organic amendments with narrow C: N ratios have a positive effect upon AM fungus proliferation compared to amendments with wider C: N ratios (Douds Jr *et al.* 1997).

While composts have been shown to be beneficial to crop production, the manufacturing process can lead to greenhouse gas emissions. Pierzynski and Gehl's (2005) review showed that while most C lost in the composting process was as CO_2, the other greenhouse gases (CH_4 and N_2O) were also released in substantial amounts. Research by Hao, Chang and Larney (2004) showed that even though application of compost to agricultural land has been reported to increase soil C content and might be regarded as a means to sequester C due to the losses during the composting process there may be little net benefit. Another risk of composting is the possible input of heavy metals and organic pollutants (such as natural androgenic and estrogenic hormones) which can be a threat to soil quality (Brandli *et al.* 2005).

The losses of N and C in the composting process may be overcome through applying additives to the compost. Possible additives might be zeolite (Kithome, Paul and Bomke 1999) or phosphogypsum (Hao, Chang and Larney 2004; Zvomuya *et al.* 2005). Phosphogypsum is a by product in the production of phosphoric acid from phosphate rock but it does contain radon gas. Zvomuya *et al.* (2005) found though that there was a significant dilution of radioactivity (to levels below limits set by Health Canada) when phosphogypsum is co-composted with cattle manure. Less risky additives such as zeolite and possibly biochar that can be either added to the compost process or applied with compost may help reduce the emissions of greenhouse gases associated with compost and manure.

2.9 OTHER SOIL AMENDMENTS

2.9.1 Zeolite

Zeolite is an insoluble and chemically stable aluminium silicate mineral that can trap, hold and exchange materials from its internal structure. Zeolite has been shown to reduce nutrient losses associated with some organic amendments. Research conducted by Kithome, Paul and Bomke (1999) found that when composted poultry manure was amended with 38% zeolite there was a 44% reduction in NH_3 losses. It has also been shown to help

counteract the effect of heavy metals in soils as zeolite can absorb heavy metals and decrease their availability to plants (Mahabadi *et al.* 2007). Mahabadi *et al* (2007) found that when it was added to cadmium contaminated soils it significantly reduced the leaching of cadmium. There has been some research into zeolite use as an amendment in cropping soils. Research by Al-Busaidi *et al.*(2008) found that zeolite can be of benefit in saline sandy soils as it can mitigate the salt stress effect on plants.

2.9.2 Biochar

Unlike compost and humus that are the remains of degradation of organic matter by biological organisms, charcoal (biochar) is the result of its incomplete combustion. There is an increasing public interest in burning organic biomass to produce a renewable source of energy and the waste product (biochar) could to be used as an aid to improve crop productivity. Research by Topoliantz *et al.* (2002) showed that wood charcoal had a beneficial effect on bean production as it decreased acidity and increased the C: N ratio in the soil. Research by Rondon (2007) found that N fixing in beans was significantly improved by addition of biochar. Other research by Glaser, Lehmann and Zech (2002), found that the addition of organic manure with charcoal has a positive long-term effect on plant growth and maintained higher oat crop yields.

Glaser *et al.* (2002) reviewed the ameliorating effects on the soil's physical and chemical properties by the addition of charcoal. They stated that it appears to aid the chemical properties of soil by raising the soil pH, so raising the nutrient availability in soil with low pH. Charcoal may also contain dissolved salts that are readily available for plant uptake as well as increasing the soils Cation Exchange Capacity (CEC). They also reported that charcoal is suspected of changing soil physical properties such as soil water retention and aggregation.

Black 'Terra Preta' charcoal based soils which are found in the Central Amazon have been shown to be more fertile than the surrounding soils (Mann 2002; Smith 1980). Glaser, Haeumaier *et al.* (2001) reported that these soils have higher soil organic matter, higher nutrient holding capacity (N, P, Ca and potassium), higher pH values and higher moisture-holding capacity than in surrounding soils. Laboratory research by Pietikainen (1999) showed that charcoal mixed with substrate-rich litter extract supported a small but more active microbial community than humus. It also indicated that there was the possibility that

charcoal has the potential to support higher microbial communities either by them attaching to charcoal directly or by the charcoal providing shelter from predators in the form of micropores as suggested by Zackrisson, Nilsson and Wardle (1996).

A summary of Japanese research by Nishio (1996) has shown that the addition of charcoal might help *Rhizobium* stimulate nutrient uptake and help growth of AM fungi in vegetation establishment on barren land. They theorized that the addition of charcoal may only have a stimulatory effect when there is a certain level of indigenous AM present. Chan *et al.* (2007) found experimentally through pot trials that there was a significant yield increase when biochar and N fertilizer are added together compared to separately. Here the rate of biochar was the equivalent to 100 t/ha. They did find significant changes in soil quality when only 50t/ha of biochar was applied. These changes included increases in pH, organic C and exchangeable cations.

The main advantage of adding biochar is that it persists in soil longer than any other form of organic matter that is commonly applied to soil creating longer lasting benefits. This property also makes it a prime candidate for the mitigation of climate change as a potential sink for atmospheric C dioxide (Lehmann 2008) although the large amounts required may be cost-prohibitive for large cropping paddocks.

2.10 CONCLUSION

This review has highlighted the many issues facing no-till farmers. These include climate change and the need to sequester more soil C and reducing emissions of greenhouse gases. Issues of soil sustainability and biodiversity were investigated to highlight their importance to many ecological processes. It was shown that increased soil biodiversity can buffer soils against many disturbances such as drought brought on by climate change. It can also play a key role in nutrient recycling, lessening the reliance on expensive fertilizers. Other benefits of increased soil biodiversity are nutrient retention and release in response to plant needs, disease suppression and enhanced soil structure and water holding capabilities. No-till farming methods were examined to evaluate their effects on soil biodiversity. It was found that despite the many benefits of no-till combating the effects of reduced or variable rainfall there are mixed responses in maximizing soil C inputs in increasing soil biodiversity.

Some research has identified that some amendments, along with their potential benefits and disadvantages may help overcome some identified problems associated with reduced soil C and soil biodiversity within the no-till environment. These roles might include improving the soil habitat for microbial growth, improving soil moisture content and levelling temperature extremes, physically providing a home for micro-organisms or adding a food source as organic C or improving CEC to hold more nutrients in the soil. The application of compost in particular was also investigated and compared it to the practice of applying manure as a nutrient source for micro-organisms. Research indicated that crop responses to biological inputs are often a result of complex interactions with significant increases in some situations and negative responses in others. There seems to be very little scientific advice available to farmers on what is the best approach for them to improve their soil biodiversity through the addition of organic amendments, especially in terms of effectiveness, amounts, cost and ease of application. It is important to have quantitative data on actual environmental benefits, as well as on yield, and whether the addition of these amendments is economically feasible especially in no-till farming systems in CW NSW. The addition of organic amendments can be expensive, especially if they do not provide real benefits to either soil health or crop productivity in both the short or long term. It is therefore important to determine specific changes in the physical, chemical and biological properties of no-till cropping soils in both high and low productive areas compared to adjacent uncultivated natural grassland soil. The examination of these changes may indicate if the addition of organic amendments is warranted.

CHAPTER 3

SOIL SURVEY OF THE EFFECT OF NO-TILL CROPPING ON SOIL PHYSICAL, CHEMICAL AND BIOLOGICAL PROPERTIES IN CENTRAL WEST REGION OF NEW SOUTH WALES AUSTRALIA

3.1 INTRODUCTION

It is estimated that up to 78% of grain growers in NSW, Australia practice no-till agriculture (LLewellyn and D'Emden 2010) making it a widely adopted method of farming. The benefits of converting to no-till have been shown, both in Australia and world-wide, to improve soil physical and chemical properties as well as increasing yields (Doran 1980b; Govaerts *et al.* 2007; Pankhurst *et al.* 1995; Radford *et al.* 1995). No-till agriculture combined with stubble retention have also been targeted as methods that farmers might use to increase soil C levels (Lal 2004; Whitbread 1996), improve earthworm burrow densities (Chan 2004), soil-dwelling invertebrates and insect predators (Robertson, Kettle and Simpson 1994) as well as improving the microbial functioning of agricultural soils (Gupta *et al.* 1994). There has been conflicting evidence about no-till's ability to increase C and microbial properties in the Australian landscape (Bell *et al.* 2006; Simpfendorfer *et al.* 2001; Watt, Kirkegaard and Passioura 2006). These properties are important if farmers want biologically diverse and active healthy soils which are more resilient to disturbance and have enhanced natural disease suppression ability (van Bruggen *et al.* 2006).

In some environments no-till agriculture has been shown to be more beneficial than conventional tillage, in terms of increasing microbial population size, activity and diversity as well as increasing soil C levels (Nsabimana, Haynes and Wallis 2004; Sun *et al.* 2011), but research in southern Queensland has shown that no-till may not address the decline in soil C, microbial abundance, structure or activity that is evident when grasslands are converted to continuous cropping (Bell *et al.* 2006). The influence that the current practice of no-till has on soils in the CW NSW is unclear. Although no-till is widely adopted as a sustainable farming practice there are varying opinions in the use of occasional tillage within the no-till system, especially when stock are involved. These opinions range from the belief that one single tillage event can revert the benefits of soil regeneration (Grandy, Robertson and

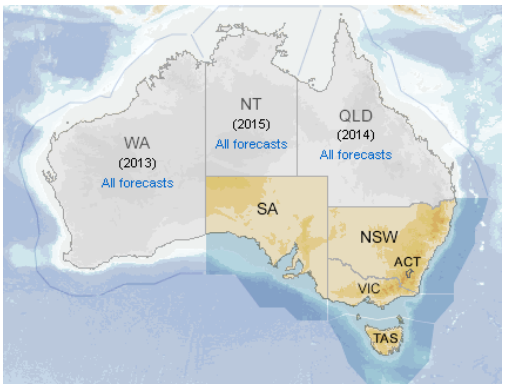
Thelan 2006) to actually being beneficial in certain circumstances (Kirkegaard *et al.* 2011). A survey was conducted within CW NSW to investigate the impact of no-till, as it is currently practiced, on microbial, chemical and physical soil properties in relation to high and low productive areas of no-till cropping areas.

3.2 MATERIALS AND METHODS

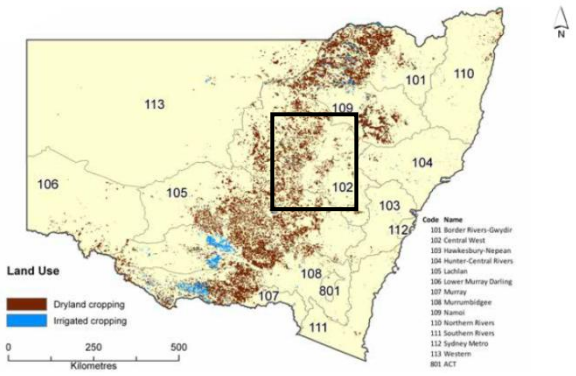
This survey was aimed at assessing biological, chemical and physical soil properties on farms in CW NSW and to determine whether current biological presence and activity may be influenced by different levels of crop production. There is a diverse range of soil types within this region but the main soil types have been identified as Chromosols, Sodosols, Kurosols, Kandosols and Vertosols. While Kandosols and Sodosols cover most of the area, the Vertosols with their relatively high clay content are an important dry-land cropping soil type and many farmers have a mosaic of red and brown clay soils on their farms (Anderson *et al.* 1999).

3.2.1 Description of survey area

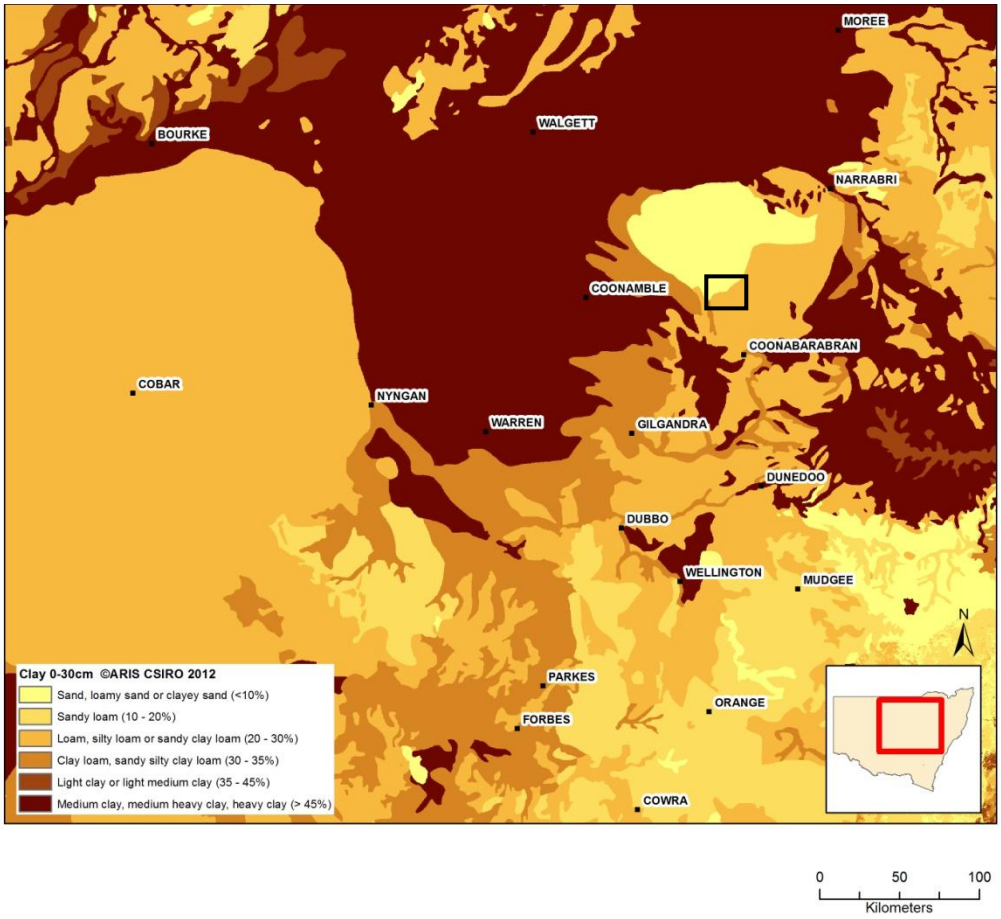
The CW region of NSW, lies within the temperate area of Australia and is a loosely defined area that extends west of the Great Dividing Range in approximately the centre of NSW (Figure 3.1). The climate is Mediterranean with hot summers and cool winters. The hottest month is January and coolest July. Rainfall spread evenly throughout the year ranging from 487 mm in Forbes to 622 mm near Merriwa (Table 3.1). It is estimated that it occupies approximately 63 000 sq km of which dryland cropping is a dominant land use feature (Figure 3.1). It was estimated that between 2007 and 2010 about 55-79% of the cropping area was not cultivated, except for herbicide spraying and sowing (Barson 2012). The predominant textural soil class within the top 0-30 cm horizon is clay based ranging from a clay loam to a heavy clay soil (Figure 3.1). The survey sites were restricted to these areas.



Source: Australian Government (2009)



Source: ABARE-BRS (2011)



Text

Source: ASRIS-CSIRO (2012)

Figure 3.1: a) Map of Australia showing location of NSW. b) Land use map of NSW showing approximate location of Central West NSW within outline rectangle. Dryland cropping areas are shaded in brown. c) Soil textural class map that includes areas of Central West NSW.

Table 3.1: Climate data for towns within survey area.

Town	Minimum Mean Annual Temperature (Celsius)	Lowest Mean Monthly Temperature and Month (Celsius)	Maximum Mean annual Temperature (Celsius)	Highest Mean Monthly Temperature and Month (Celsius)	Annual Mean Rainfall (mm)
Coonamble	11.5	3.5 (July)	26.3	35.2 (January)	554.0
Dubbo	10.2	3.1 (July)	24.4	33.4 (January)	569.3
Trangie	10.8	3.2 (July)	24.6	33.3 (January)	494.3
Forbes	9.6	2.5 (July)	24.4	34.5 (January)	487.2
Merriwa	9.0	1.9 (July)	22.2	29.5 (January)	622.4

Source http://www.bom.gov.au/climate/data/index.shtml?bookmark=200

Sites for soil testing were selected on commercial farms within this area. These farms were located between Coonamble in the north, Merriwa in the east, Forbes in the South and Trangie in the West (Figure 3.2). Clay textured soils were selected for testing that had been cropped recently using no-till farming methods. The surveys were undertaken from April to June in 2008 and 2009. At this time of year the cropped soils had either a previous winter or summer stubble and were being prepared for a following winter crop.

During autumn of 2008 and 2009 prior to annual winter planting twenty sites each year within this region were selected to be tested, giving a total of 40 sites tested over the two year period. The sites selected were through contacts with no-till farming groups, agronomic groups or through personal contacts. The criteria for selection was that the sites to be managed under the broad definition of no-till and that the cropping paddocks were of clay texture with known low and high productive areas within it and to have in close proximity a non-cropped area of similar soil type. Identification of productivity areas was done by examining yield harvest maps and/or discussion with farmer's background knowledge and experience along with visual signs such as condition of previous stubble. The non-cropped site was selected so to have the same soil type and topographic position, a soil that had never been cultivated that could be used as a reference area. These non-cropped reference sites were fence lines, roadsides or adjacent paddocks that may have been lightly grazed but have never been used for growing crops. Preference was given to areas that were within 100 m of the cropping site. Within the cropping paddock one location was identified by the owner where the previous crop had a high level of crop production and another where it was lower.

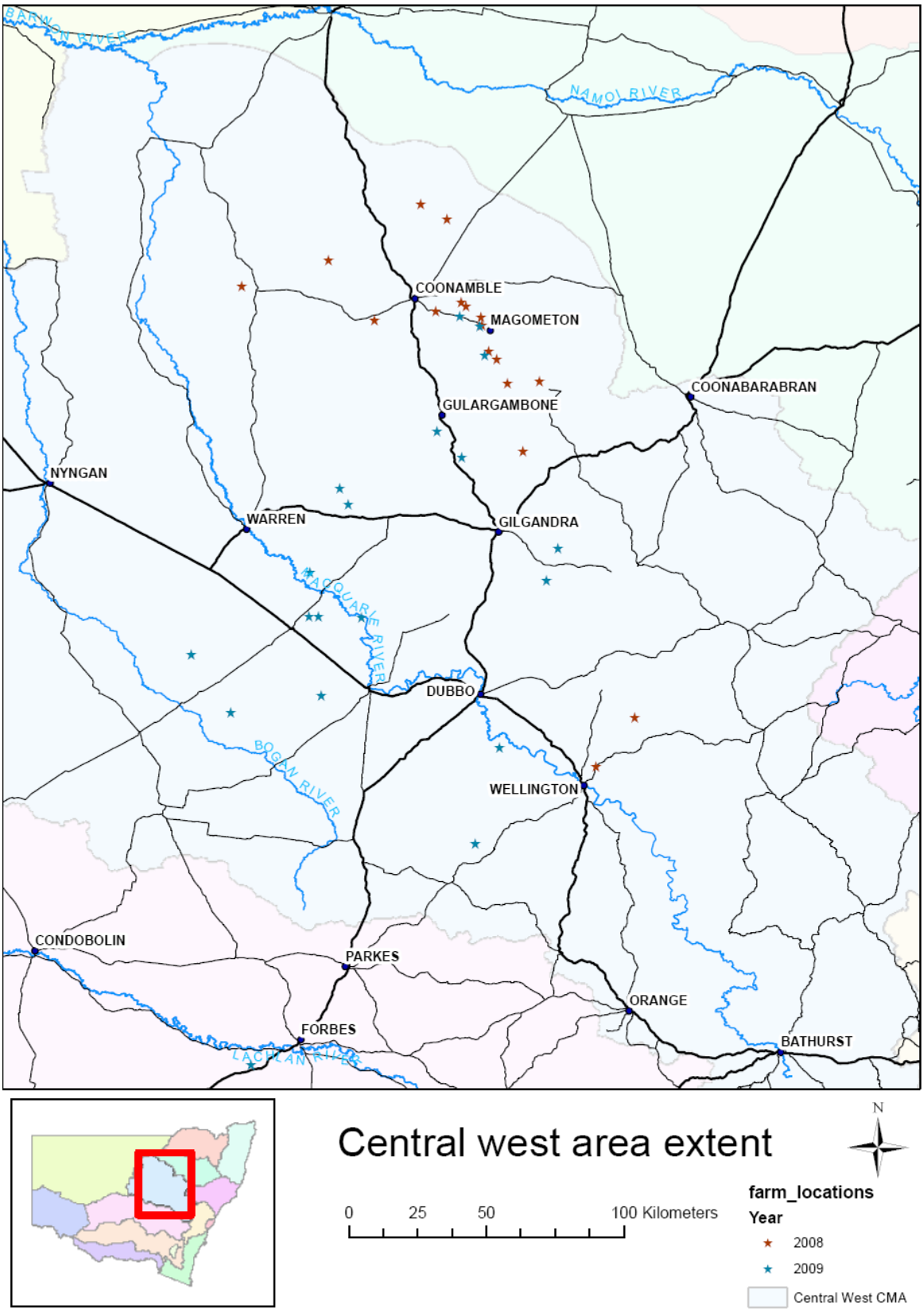


Figure 3.2: Locality map of the Central West NSW indicating location of farm survey sites

3.2.2 Sampling design

To limit the effect of seasonal variation on these results, the sites were sampled during a similar phase in the cropping cycle during a similar time of year. The areas on each farm to be tested were selected to be reasonably close to limit the influence of rainfall variability and other environmental differences between the low and high productive cropped areas with their reference sites. The area to be tested was to be representative of either a typical high production or low production area of the cropping paddock. All three sites on each farm had to meet the criteria that it had typical characteristics of the cropping paddock such as similar soil texture and topographic features.

On each of the three sites on 20 farms in 2008 and a different 20 farm sites in 2009 soil samples were taken and Global Positioning System (GPS) coordinates recorded. The soil samples to a depth of 5cm were taken within a 5x5 m grid which was representative of the soil area. Other measurements such as percentage of ground cover, soil moisture and penetrometer recordings were also recorded. A cropping and management history was collected from the farmers.

3.2.2.1 Cropping and management background

There were a wide variety of farming practices occurring on the surveyed soils, but 45% had been continuously winter cropped during the previous five years. The most common system used as defined by the participants was no-till without stock on the paddock (Table 3.2); using a winter cereal, oilseed and pulse rotation (Table 3.4); and using chemcial fertilizer; knockdown and residual herbicides with traffic movement controlled by auto steer technology which enabled machinery to be automatically driven in straight lines with the use by GPS (Table 3.3).

Table 3.2: Types of cropping systems surveyed

Cropping System	Without Stock (%)	With Stock (%)
No-Till	85	10[A]
Minimum Till[B]	2.5	2.5

[A]50% of these had annual crops sown into summer perennial grasses; [B] Defined by occasionally using a one off cultivation

There was a diverse range of crop rotations ranging from simple monocultures to more diverse crop types (Table 3.4) with cereals (mainly wheat) being the most common crop grown (Table 3.5). Pulses (mainly chickpeas) were more common than oilseeds (mainly canola) (Table 3.5). During the summer periods there was a small percentage of paddocks that had pastures or summer crops of sorghum, millet or sunflower (Table 3.4) with the rest chemically sprayed to control weeds for the following winter crop. Just over 10% of the paddocks had livestock on them at some stage during the year (Table 3.2).

Table 3.3: Management on cropped soil survey sites.

Stubble Management [a]			
Standing (%)	Burnt (%)	Grazed (%)	Cultivated (%)
69	2.5	16	12.5
Traffic movement [a]			
Autosteer (%)	Guidance with a light Bar (%)	Guidance with Marked lines (%)	Random (%)
49	10	18	23
Annual Winter Crop Types [b]			
Cereal, Pulse and Oilseeds (%)	Cereal and Pulses (%)	Cereal and Oilseeds (%)	Cereal Only* (%)
32	24	6	39
Annual Summer Crop Types [b]			
Sorghum (%)	Millet (%)	Sunflower (%)	
11	10	3	
Fertilizer Type [b]			
Chemical (%)	Organic (%)[c]	Nil (%)	
56.5	21	22.5	
Chemical Usage [a]			
Knockdown Herbicides (%)	Residual Herbicides (%)	Insecticides (%)	Fungicides (%)
95	73	20	22

* Includes cereals and pasture (mainly Lucerne).[a] During previous 12 months. [b] During previous 5 years.
[c] Organic refers to manure or compost fertilizers

Generally, knockdown and residual herbicides were more commonly used on cropped paddocks than insecticides or fungicides (Table 3.3). A very small sample (about 5%) of the

cropped paddocks did not have any applications of fertilizer, herbicides, fungicides or insecticides applied in the last five years but these only had at most 2 crops grown during that time with a pasture phase during the remainder years.

Table 3.4: Winter Crop rotations on cropped paddocks

Crop Rotation	Paddock (%)
Cereal only	21
Cereal, pulse,	21
Cereal, pulse, pasture	3
Cereal, pulse, oilseed	31
Cereal, pasture	18
Cereal, pasture, oilseed	3
Cereal, oilseed	3

Table 3.5: Frequency of crop type

	Previous crop	Mean times grown in last 5 years
Cereal[a]	66%	2.84 (wheat =2.18)
Pulse[b]	10%	0.65
Oilseed[c]	8%	0.41
Summer[d]	16%	0.36
Winter Fallow[e]		0.32
Pasture[f]		0.49

[a] Cereal included wheat, barley, oats and triticale
[b] Pulse crops included chickpeas and field peas
[c] Oilseeds included canola and linseed
[d] Summer crops comprised sunflowers, sorghum, millet
[e] Paddocks were chemically fallowed to prevent plant growth
[f] Pastures were either sown (Lucerne) or left to regenerated

3.2.3 Soil analyses

At least 10 individual soil samples were collected from each site, mixed together and divided into 200g bags and refrigerated. On completion of collection of all samples one group was posted to the Environmental Analysis Laboratory (EAL), University of Lismore to be commercially analysed by their chemistry department. Samples from a subgroup of 3 farms in 2008 and from all 20 farms in 2009 were posted to the Lismore Soil Foodweb institute for a commercial analysis of microbial diversity and activity to be done by their staff. Samples

from a subgroup of 5 farms in both 2008 and 2009 were transported to the University of New England (UNE) for microbial biomass and respiration testing. Another lot of soil samples, collected with a 5 cm diameter core ring, were transported to UNE for particle size analysis. In field measurements such as penetration resistance, percentage of soil cover and moisture content were recorded at the time of soil sample collection.

3.2.3.1 Analysis of soil microbial biomass and respiration

Soil was gently broken down into smaller pieces with all foreign matter such as stones, roots and any visible soil biota removed. For each soil sample about three subsamples weighing 80 g were put into respirometer pots. The soil moisture was then adjusted to 75g/100g field capacity for optimal microbial respiration. The soil in the respirometer pots was then incubated at 20^{o}C for two days then placed in a water bath also at 20^{o}C in a respirator. The CO_2 evolution was measured by an electronic respirometry system (Respicond®, [1]Nordgren Innovations AB, Umea, Sweden).

Average basal respiration was measured over 48 hours (mg/CO_2/hr/100g DM soil). The microbial biomass was determined by the Substrate-Induced Respiration (SIR) method (Anderson and Domsch 1978). This involved mixing in 0.22g glucose substrate and recording the increase in respiration rate and from that the amount of microbial C in soil is calculated (mg microbial C/ a100g DM soil).

The values obtained by measurement for soil microbial biomass and respiration were used in several calculations to determine three microbial indices. These were the respiratory or metabolic quotient q(CO_2), microbial quotient (%) and ratio of respiration to Total C (%). The metabolic quotient q(CO_2) is the ratio of microbial respiration to microbial biomass which calculates the amount of CO_2- C produced per unit of microbial biomass C (unit CO_2-C unit^{-1} biomass-C h^{-1}) (Anderson and Domsch 1986). The microbial quotient was calculated by dividing microbial biomass C by the percentage of total C.

3.2.3.2 Soil microbial community structure

The soil samples sent to the Lismore Soil Foodweb institute were analysed for an estimation of the total and active bacterial and fungal biomass as well as an estimation of the

microscopic protozoa and nematode population by light microscope, a commercial service available to farmers in the region. Nematodes were extracted from the soil by a modified Baermann funnel method (Ingham 1994b) then counted and identified using a compound microscope. Protozoan enumeration was achieved by direct observation methods using interference contrast microscopy (Ingham 1994a). Estimations of microbial population sizes were based on the most probable number counting techniques (MPN) (Woomer 1994).

An in-depth analysis of the nematode population was undertaken from received information on the identified nematode genus in the commercial report. The nematodes were re-allocated to feeding group based on 1 = bacterial feeding, 2 = fungal feeding, 3 = predatory, 4 = plant feeding, 5 = plant associated and 6 = omnivorous (Yeates and King 1997; Yeates, Bongers *et al.* 1993) as well as grouped according to cp (coloniser or persister) classifications with values ranging from 1 to 5. The cp gradient is based on the nematodes r-k strategy with colonizers (r strategists) and persisters (k strategists) being the extremes from 1 to 5 respectively (Bongers 1990; Bongers and Bongers 1998). These classifications were then used to calculate some general indices used as an indicator of nematode diversity (Yeates 2003; Yeates and Bongers 1999). These indices included the Shannon-Wiener index (H') which is used as an indication of diversity as well as evenness (J') richness (SR) and dominance (λ) as defined by Yeates and Bongers (1999).

These indices were calculated using the following formulae:

Where *N* is the number of individuals identified;

S is the number of taxa identified; a given taxon is regarded as the *i*th taxon;

P is the proportion of individuals in the *i*th taxon.

diversity $H' = -\sum pi \log_e pi$ (i from 1 to S)

evenness $J = H'/ H'_{max}$ where $H'_{max} = \log_e S$

richness $SR = (S - 1)/ \log_e N$

dominance $\lambda = \sum p_i^{\,2}$

Other indices used were the nematode channel ratio [NCR = B/ (B+F)] where B refers to the population size of bacterial-feeding nematodes and F fungal-feeding nematodes. The ratio lies between 0 and 1 with 0 indicating that the plant decomposition pathway is totally fungal dominate and 1 indicating that it is totally bacterially dominated (Yeates 2003). The

maturity index ∑MI which is a measure of successional status of the soil community (Bongers 1990) was calculated using the formula:

$\sum (cp_i \times i)$/ number of nematodes identified where i is the cp number from 1 to 5.

3.2.3.3 Soil physical parameters

Measurements of ground cover, soil strength and soil moisture were taken in the field. Ground cover was accessed by throwing a 10 cm x 10 cm square ring onto the ground surface 10 times and the percentage of the ground covered by residues was estimated. Soil strength was estimated by using a penetrometer and soil moisture using a MP406 Soil Moisture Sensor probe. At UNE the percentage of clay, silt and sand in each sample was obtained by particle size analysis. The method included using 11 g of prepared soil that was air dried and sieved to less than 2 mm and then placed in 5 cm plastic tubes with 50 ml of dispersion agent. The agent was 9.1 g Sodium Carbonate 9.1 g, 46.9 g Sodium Hexameta phosphate mixed to 2 litres. After tumbling overnight, the agent was added to a plastic cylinder halved and filled with distilled water. A plunger was used to stir the mixture. Using Stokes law, the temperature was used to determine period of rest and about 25.46 ml of soil water was decanted into aluminium dishes which were then dried at 105 degrees C. The process was repeated after 4 hours. The net weights of dried soil in each of the two dishes were used to determine percent silt and clay and the percentage sand was calculated by difference.

3.2.3.4 Soil chemical parameters

Soil samples sent to the EAL laboratory were examined for a complete chemical analysis that is commercially available to farmers within CW NSW. The report was based on Albrecht and Reams soil analysis package. Total C % and total N % was measured using a LECO CNS Analyser. Soluble Ca, Mg, K, and P were tested using modified Morgan extract (Anderson, 2000) while the other tests including Bray 1 and Colwell phosphorous were conducted using techniques from Albrecht Methods (Rayment and Higginson 1992).

3.2.4 Statistical analyses

For each data set normality indicators were checked and, where appropriate, transformation of data was done to achieve normality. Homogeneity and independence of variables were then checked in the transformed data. In order to reduce the risk of Type I statistical errors in large group data sets a multi-variate canonical variate (CV) analysis was conducted where appropriate to determine linear combinations of the data variates that represented most of the variation between the groups of data. The variables with the highest latent vectors were then selected for further analysis by ANOVA. Tukey multiple comparison (TMC) tests were applied to identify significance between factor means (Neter *et al.* 1996). Some data was checked using generalized linear models (GLM). If normality conditions were satisfied but homogeneity and independence of variances were not met by transformations and/or deleting farms that had indications of effects of some extrinsic influence then a weighted least squares analysis was performed (Neter *et al.* 1996) to determine if the factor means differed. When transformations failed to produce normality and homogeneity and independence of variances then non-parametric analysis was undertaken (Neter *et al.* 1996). This involved conducting, for each parameter, an overall ANOVA carried out by the non-parametric Kruskal-Wallis method and a Mann-Whitney pairwise site comparison on those factors found to be significant. The Kruskal-Wallis rank test is equivalent to the rank F test statistic using H as the test statistic representing the variance of group ranks not means, with degrees of freedom (df) equal to 1 minus the number of groups (Neter et al. 1996).

The Genstat statistical computer package was used for all statistical analysis.

3.3 RESULTS

3.3.1 Soil physical and abiotic parameters

In both 2008 and 2009 non-cropped soils had a higher percentage of ground cover and had higher soil strength in the top 0-5 cm of soil (Table 3.6). Penetration resistance was found to be higher at all depths in non-cropped soils (Figure 3.3). In 2009, cropped soils had a higher percentage of moisture in the top 5 cm and 5-10 cm region of the soil than non-cropped soils. In 2008 soil moisture did not differ between cropped and non-cropped soils.

There was not a significant difference between the percentage of clay, silt or sand between the cropping and non-cropped soils (Table 3.6).

Table 3.6: Results of physical characteristics found on paired sites on soils in CW NSW.

	Non-cropped Soils (NC)	Higher productive cropping soils (CH)	Lower productive cropping soils (CL)
		2008	
Soil texture			
Clay (%)	43.4	49.5	43.0
Silt (%)	2.6	3.8	2.9
Sand (%)	54.0	46.7	54.1
Moisture (%)			
0-5cm	19.4	20.9	18.3
5-10cm	21.1	24.4	21.9
Ground cover (%)	84.1 a	40.5 b	36.4 b
Penetration resistance (kpa)	2594 a	1888 b	2089 b
		2009	
Soil texture			
Clay (%)	43.4	45.3	42.9
Silt (%)	4.6	5.8	5.3
Sand (%)	52.0	48.9	52.2
Moisture (%)			
0-5cm	8.5 a	15.0 b	12.3 b
5-10cm	14.9 a	22.0 b	19.5 b
Ground cover (%)	82.9 a	63.3 b	42.5 c
Penetration resistance (kpa)	3265 a	2002 b	2515 b

Means followed by the same letter across sites are not significantly different according to TMC at P≤0.05

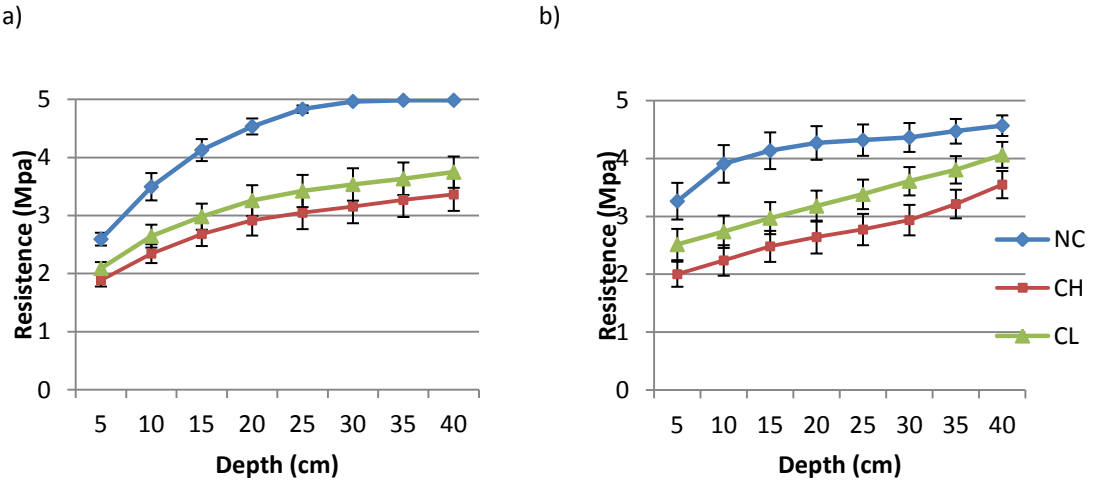


Figure 3.3: Soil penetration resistance for (a) 2008 (b) 2009. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

3.3.2 Soil chemical properties

A CV analysis was conducted to determine possible differences between the three soil reference types and which combination of variables contributed to such differences. This analysis shows that the combination of chemical properties significantly ($P < 0.05$) differ between cropped and the non-cropped reference soils as denoted by the distance separated between them along the y-axis (Figure 3.4). The y-axis reflects chemical parameters defined by the 1st canonical variates (CV_1) (Table 3.7). In both 2008 and 2009, CV_1 accounted for 69% and 83% of the variation between cropped and non-cropped reference soils respectively (Table 3.7). The major contributors to CV_1 in both years were total N and C %. In 2008 Boron and exchangeable sodium (ex Na) were also major contributors and in the 2009 survey iron and manganese were the major contributors (Table 3.7).

A following ANOVA analysis of these selected variables (Table 3.8) suggested that total C %, total N %, Mn and Fe values were significantly different between non-cropped and cropped soils in both years. Total C % and total N % levels were reduced in cropped soils by at least 35% and 33% respectively in both years (Table 3.8).

Table 3.7: Values of latent vectors with values >1 or< -1 resulting from a CVA on chemical parameters.

Parameter	Year:	2008		2009	
		1st Canonical variate	2nd Canonical variate	1st Canonical variate	2nd Canonical variate
	Variation (%)	69.03	30.97	83.52	16.48
Boron (ppm)		-3.223	5.065	*	*
Total N (%)		1.392	89.149	-54.907	-15.104
Total C (%)		1.279	-5.371	4.319	*
Ex Na (cmol/kg)		-1.976	3.592	*	1.329
K (cmol/kg)		*	-5.381	*	4.118
pH (water)		*	-1.066	*	1.657
Ammonium (ppm)		*	-1.170	*	*
Sulphate (ppm)		*	1.633	*	*
Fe (ppm)		*	*	-2.029	*
Mn (ppm)		*	*	-1.200	*

* CV value -1<CV < 1; Parameters that were tested but had both 1st and 2nd CV values between -1 and 1 for both years were omitted here and from further analysis.

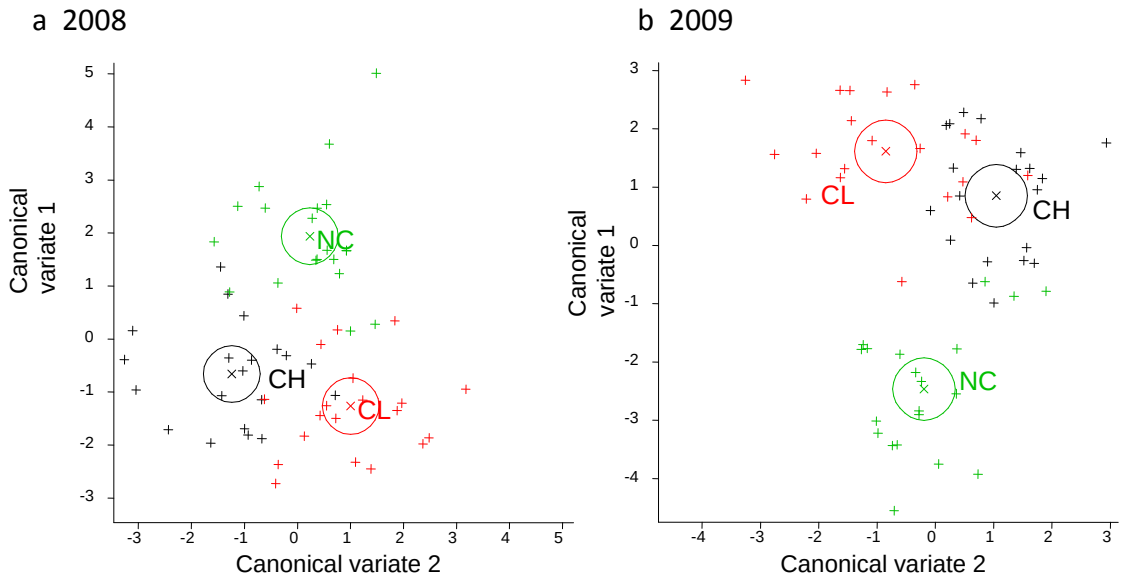


Figure 3.4: Plot of canonical variates (CV) generated by canonical analysis of all measured soil chemical properties showing discrimination between cropped (high productive area denoted by CH and lower productive areas denoted by CL) and the non-cropped reference (NC) soils showing a 95% confidence region around the mean for a) 2008 b) 2009.

The 2nd canonical variate (CV_2) explained 31% and 17% of the variation between productive sites of cropping soil for 2008 and 2009 survey respectively (Table 3.7). This variation outlined graphically is demonstrated by the distance apart on the x-axis (Figure 3.4). The CV_2 variate appears to explain variation between cropping productivity sites more than between cropped and uncropped soils. While the CV_2 consisted of total N %, exchangeable Na, K and soil pH (Table 3.7), the ANOVA showed that individually these differences were not significant in either year (Table 3.8). Although ex Na values were higher in lower producing cropped areas in both years this difference was only significantly higher in the 2009 survey. Similarly the ex K levels were lower in lower producing crop areas but only significantly lower in 2009. Total N percentages and soil pH were slightly lower in low producing areas but these values were not significant. In addition, 2008 boron levels were significantly higher in the lower producing crop areas and in 2009 there was a decrease in total C % (Table 3.8).

The correlations between soil C and N with soil physical characteristics are shown in Table 3.9. In both 2008 and 2009 total C % and total N % were highly correlated with each other

and both were highly and significantly positively correlated to the percentage of ground cover (Table 3.9). All three of these variables were lower in cropping soils in both years. In 2008 both total C and total N were significantly positively correlated to soil strength but only total C % was significantly positively correlated in 2009. In 2008 total N was positively correlated to clay (%). In both surveys particle size and moisture levels were not correlated to total C %, but moisture was positively correlated to clay content and negatively correlated to soil strength as measured by penetration resistance (Table 3.9).

Table 3.8: The effect of cropping practices on soil chemical properties.

	NC	CH	CL	NC	CH	CL
	2008			**2009**		
Parameter						
Boron	0.6 a[A]	0.5 b	0.6 a	0.7	0.7	0.7
Total C (%)	2.0 a	1.3 b	1.3 b	2.3 a	1.5 b	1.2 c
Total N (%)	0.15 a	0.10 b	0.09 b	0.19 a	0.13 b	0.11b
K (cmol/kg)	2.1	2.0	1.9	1.8 a	1.8 a	1.4 b
Na (cmol/kg)	0.52	0.42	0.55	0.32 a	0.36 a	0.55 b
pH (water)	6.7 a	7.0 b	6.7 ab	6.2	6.4	6.2
NH_4 (ppm)	2.4 a	1.2 b	1.2 b	3.1 a	1.8 b	1.7 b
Sulphate ppm	9.3	8.6	8.9	9.9 a	7.6 b	7.6 b
Mn ppm	47.5 a	31.8 b	29.9 b	39.0 a	27.1 b	35.1a
Fe ppm	63.6 a	49.7 b	50.2 b	82.0 a	49.9 b	58.6 b

[A] Means followed by the same letter within rows for each year are not significantly different according to TMC at P≤0.05. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

Table 3.9: Correlation coefficients for measured soil physical characteristics in relation to total C and total N

	Ground Cover (%)	Clay (%)	Moisture (%)	Penetration resistance (Kpa)	Total C (%)	Total N (%)
			2008			
Ground cover (%)	1					
Clay (%)	n.s.	1				
Moisture (%)	n.s.	0.23*	1			
Penetration resistance (Kpa)	0.23*	n.s.	-0.48***	1		
Total C (%)	0.49***	n.s.	n.s.	0.28*	1	
Total N (%)	0.49***	0.23*	n.s.	0.3*	0.96***	1
			2009			
Ground cover (%)	1					
Clay (%)	0.26*	1				
Moisture (%)	n.s.	0.44***	1			
Penetration resistance (Kpa)	n.s.	n.s.	-0.7***	1		
Total C (%)	0.41***	n.s.	n.s.	0.32*	1	
Total N (%)	0.41***	n.s.	n.s.	n.s.	0.96***	1

* p-value < 0.05 ** p-value < 0.005 ***p-value < 0.0005 n.s. not significant

3.3.3 Soil biological parameters

3.3.3.1 Soil microbial biomass carbon (SMB C) characteristics

SMB C and respiration properties were investigated on a subset of 5 farms in both 2008 and 2009. SMB C in cropped soils was at least 58% lower in 2008 and 43% lower in 2009 compared to the non-cropped reference soils (Table 3.10). Respiration was significantly reduced in cropped soils in 2008 only. There was no significant difference in SMB C or respiration between the higher and lower productive cropped soils in either 2008 or 2009 (Table 3.10).

Table 3.10: Soil SMB C and microbial respiration for 5 farms in 2008 and 2009.

Land Use	Respiration (mg CO_2/hr/100 g DM soil)		Microbial Biomass (mg Microbial Carbon/100 g DM soil)	
	2008	2009	2008	2009
NC	0.56 a[A]	0.30	106.6 a	58.9 a
CH	0.32 b	0.12	45.2 b	32.4 b
CL	0.27 b	0.15	40.0 b	31.8 b

[A] Means followed by same letter within columns are not significantly different according to TMC at P≤0.05. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

3.3.3.2 Microbial ratios

Microbial ratios for 2008 and 2009 (Table 3.11) indicated that there was a consistent significant decrease of the microbial quotient (amount of microbial biomass per unit of total C %) in the higher producing cropped soil compared to non-cropped soil but in the lower producing cropped soil this reduction was only significant in the 2008 survey. In the 2009 survey there was a significant decrease in the amount of respiration per unit of total C % in the higher producing cropping soils compared to non-cropped soils but the decrease was not significant in the 2008 survey. There were no significant differences in the metabolic quotient q (CO_2) (ratio of respiration to microbial biomass) in either year.

Table 3.11: Microbial indices for 5 farms in 2008 and 2009.

Land Use	Respiratory (or metabolic quotient q(CO_2)) x10^3	Respiration: % total C	Microbial quotient (%) (Microbial Biomass: % total C)
		2008	
NC	6	0.36	0.60 a
CH	8	0.25	0.35 b
CL	7	0.23	0.34 b
		2009	
NC	5	0.23 a	0.46 a
CH	4	0.05 b	0.13 b
CL	9	0.10 ab	0.20 ab

[A] Means followed by same letter within columns are not significantly different according to TMC at p≤0.05. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

3.3.3.3 Microbial community structure

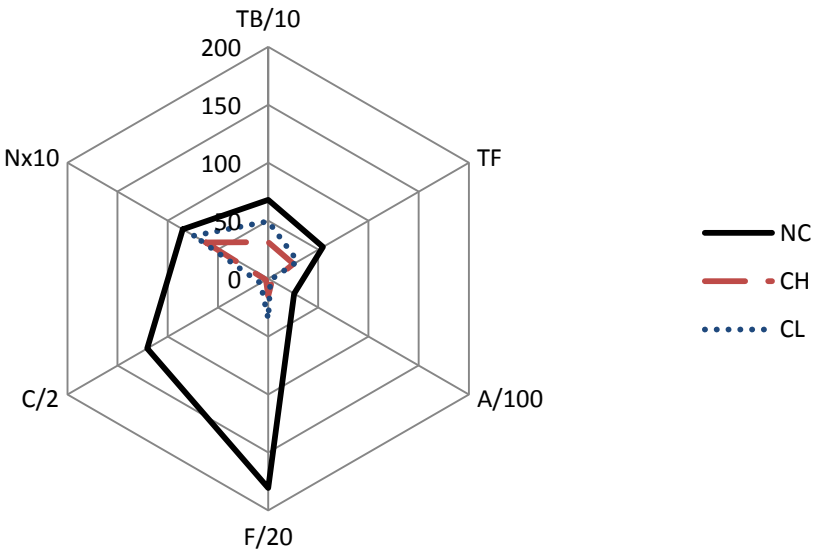
In both 2008 and 2009 all farms were tested for abundance and genera of nematodes. There was a 205% ($P < 0.005$) increase in the total abundance of nematodes in the higher productive soils compared to non-cropped reference soil in 2009 (Tables 3.11 & 3.12). In a preliminary examination of the bacterial, fungal and protozoan microbial community structure three out of the 20 farms in 2008 were tested for possible differences between sites. This small subset did not pick up any significant differences despite what looked like a possible overall reduction in microbial community structure especially in the reduction of flagellate and ciliate populations due to cropping (Table 3.12 and Figure 3.5). A more extensive survey in 2009 did not replicate this pattern except that the total fungal biomass

was reduced in both years (Table 3.12 and Figure 3.5). The non-parametric ANOVA analysis of the 2009 data indicated a significant reduction of total fungi biomass by at least 49% ($P < 0.005$) in both higher and lower productive cropped soils compared to non-cropped reference soil (Table 3.12). Fungal activity was also reduced in cropped soils with a 64% ($P < 0.005$) reduction in higher productive soils and 15% ($P < 0.025$) in lower productive soils compared to the non-cropped reference soils. There was also a significant 57 % reduction of fungal activity in higher productive compared to soils that produced lower productive crops (Table 3.12). There were no significant differences between actinobacteria and endo mycorrhizal fungi mean values but there were as few as 12 % sites having endomycorrhizal fungi and 43% having actinobacteria present.

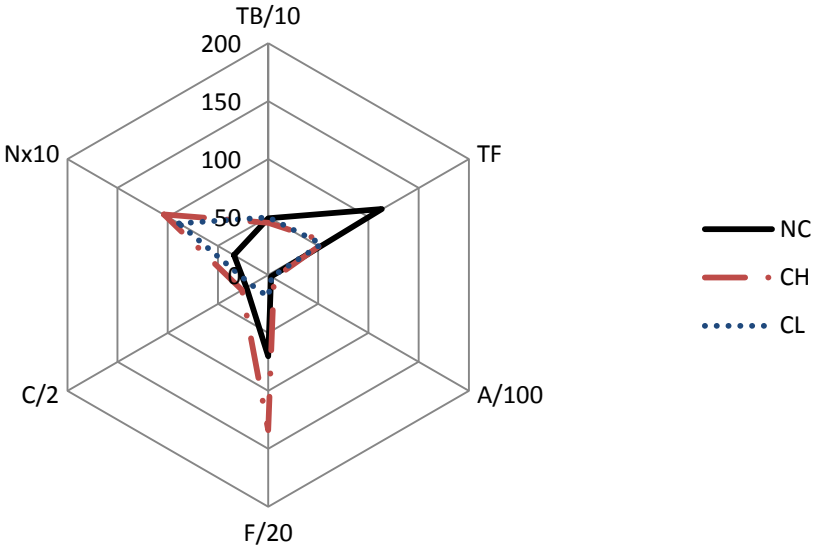
Table 3.12: Microbial community soil analysis

	2008 (n= 3)			2009 (n= 20)		
Land Use	NC	CH	CL	NC	CH	CL
Active Bacteria (μg/g)	49.8±10.8*	36.2±13.8	24.6±10.5	24.68±2.3	19.37±1.9	18.93±1.8
Active Fungi (μg/g)	11.6±10.7	1.6±0.8	2.3±0.5	5.52±1.04	2.0±2.02	4.7±2.01
Total Bacteria (μg/g)	679±103	313±153	494±105	487.8±37.5	450.7±33.9	496.9±51.4
Total Fungi (μg/g)	54.6±29.4	25.2±14.1	29.6±9.6	113.4±19.0	57.3±8.7	53.51±10.4
Actinobacteria (μg/g)	1.3±1.3	0.4±0.1	0	1.97±0.88	0.47±0.19	0.52±0.19
Endo mycorrhizal (%)	0	0	0	0.50±0.5	1.1±0.7	2.2±1.7
Amoeba (no./g)	2602±1426	388±268	225±60	298±88.6	572.8±179	364.3±168
Flagellates (no./g)	3613±1778	299±174	699±508	1404±916	2680±1858	375.8±98.5
Ciliates (no./g)	241±192	4.3±2.2	15.3±12.0	43.4±16.7	52.2±17.1	33.9±5.8
Nematodes (no./g)	8.5±1.5	6.2±1.4	7.4±1.31	3.4±0.8	10.4±2.5	8.9±2.3

*Means ± standard errors. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.



a 2008



b 2009

Figure 3.5: in 2008 (n=3) and 2009 (n= 20). TB/10 =Total Bacterial biomass divided by 10; TF= Total Fungal biomass; FLA/20; Flagellates =divided by 20; AM/100=Amoebae divided by 100; CIL/2= Ciliates divided by 2; NEM=nematodes. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

Table 3.13: Active and total bacteria and fungal biomass (µg/g dry soil), protozoa and nematodes population size (no. /g dry soil).

a. Active bacteria

2008	**2009**
n.s.	n.s.

b. Total bacteria

2008	**2009**
n.s.	n.s.

c. Active fungi biomass

2008	**2009**
n.s.	H = 14.36 p<0.001

CH			
CL	**(CL>CH)		
NC	***(NC>CH)	**(NC>CL)	
	CH	CL	NC

d. Total fungi biomass

2008	**2009**
n.s.	H = 11.8 p=0.003

CH			
CL	n.s.		
NC	***(NC>CH)	***(NC>CL)	
	CH	CL	NC

d. Amoebae

2008	**2009**
n.s.	n.s.

e. Flagellates

2008	**2009**
n.s.	n.s.

f. Ciliates

2008	**2009**
n.s.	n.s

g. **Total nematodes**

2008	**2009**
n.s.	H = 7.935 p=0.019

CH			
CL	n.s.		
NC	***(CH>NC)	n.s.	
	CH	CL	NC

For each parameter, overall ANOVA is carried out by the non-parametric Kruskal-Wallis method and pairwise site comparisons by one-tailed Mann-Whitney. *$P < 0.05$; **$P < 0.025$; ***$P < 0.005$. Letters in brackets refer to the sites. ns, not significant (p>0.05). H represents the variance of the ranks among the groups, approximately chi-square distributed with degrees of freedom 1 less than the number of groups (McDonald 2009). NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

Table 3.14: The correlation between protozoa, their prey and abiotic factors

	Flagellates	Amoebae	Ciliates
AB	↑**	n.s.	↑*
AF	n.s.	n.s	n.s.
TB	n.s.	↑*	n.s.
TF	n.s.	n.s	n.s.
Clay %	n.s.	n.s.	n.s.
Soil pH	n.s.	n.s.	n.s.
Field moisture (%)	↑*	↑***	↑*
Total N (%)	n.s.	n.s.	n.s.
TOTAL C (%)	n.s.	n.s.	n.s.
C:N	n.s.	n.s.	n.s.

[Significant levels (***) p< 0.0005; (**) p< 0.005; (*) p<0.05; n.s. = not significant, ↑ = increase]. AB refers to active bacterial biomass; AF refers to active fungal biomass; TB refers to total bacterial biomass; TF refers to total fungal biomass; TN refers to total nitrogen.

Levels of protozoa are correlated with soil moisture levels and availability of prey (Table 3.14). It appears that as soil moisture levels increased in these surveys the number of flagellates and ciliates increased along with the amount of active bacterial biomass and the number of amoebae increased with the amount of total bacterial biomass (Table 3.14).

3.3.3.4 Bacterial and fungi ratios

In 2009 the ratio of total fungal to total bacterial biomass (TF: TB) was significantly ($P < 0.05$) reduced in both higher producing and lower producing areas of cropped soils compared to non-cropped reference soils (Table 3.16) by approximately 38% (Table 3.15). The activity of bacteria compared to total bacteria biomass (AB: TB) was significantly ($P = 0.046$) reduced in the lower producing cropping soils compared to non-cropped reference soils (Table 3.16) by approximately 58% (Table 3.15).

Table 3.15: The effect of land use on bacterial and fungi ratios

	TF: TB	AB: TB	AF: AB	AF: TF
Land Use			2008	
NC	0.07 ± 0.03*	0.07 ± 0.01	0.18 ± 0.16	0.22 ± 0.10
CH	0.08 ± 0.01	0.14 ± 0.06	0.03 ± 0.02	0.07 ± 0.01
CL	0.06 ± 0.03	0.05 ± 0.01	0.12 ± 0.04	0.10 ± 0.03
			2009	
NC	0.29 ± 0.04	0.12 ± 0.04	0.23 ± 0.04	0.05 ± 0.01
CH	0.18 ± 0.04	0.05 ± 0.01	0.10 ± 0.03	0.03 ± 0.01
CL	0.18 ± 0.04	0.05 ± 0.01	0.21 ± 0.06	0.02 ± 0.02

* Means ± se. 2008 n=3; 2009 n=20. TF refers to total fungal biomass; TN refers to total bacterial biomass; AB refers to active bacterial biomass; AF refers to active fungal biomass; TF refers to total fungal biomass

The ratio of the active fungal to active bacterial biomass (AF: AB) was significantly lower in higher productive cropped soils compared to non-cropped soils ($P < 0.0005$) as well as to lower productive cropped soils ($P < 0.005$) (Table 3.16) by 52% and 9% respectively (Table 3.15).

The ratio of active fungi to total fungi biomass (AF: TF) was significantly reduced in higher productive cropped soil compared to non-cropped soil ($P < 0.05$) as well as to lower productive cropped soil ($P < 0.005$) (Table 3.16).

Table 3.16: The effect of landuse on microbial ratios in 2009

a **Ratio of active bacteria to total bacteria (AB: TB)**

2008 **2009**

H= n.s. H= 6.044 p=0.47

CH			
CL	n.s.		
NC	*(NC>CH)	* (NC>CL)	
	CH	CL	NC

b **Ratio of active fungi to active bacteria (AF: AB)**

2008 **2009**

H= n.s. H=11.43 p=0.003

CH			
CL	** (CL>CH)		
NC	***(NC>CH)	n.s.	
	CH	CL	NC

c **Ratio of total fungi to total bacteria (TF: TB)**

2008 **2009**

H= n.s. H=7.897 p=0.019

CH			
CL	n.s.		
NC	*(NC>CH)	**(NC>CL)	
	CH	CL	NC

d **Ratio of active fungi to total fungi (AF: TF)**

2008 **2009**

H= n.s. H=9.359 p=0.009

CH			
CL	** CL>CH)		
NC	* (NC>CH)	n.s.	
	CH	CL	NC

For each parameter, overall ANOVA was carried out by the non-parametric Kruskal-Wallis method and pairwise site comparisons by one-tailed Mann-Whitney. *$p < 0.05$; **$p < 0.025$; ***$p < 0.005$. Letters in brackets refer to the sites. n.s, not significant (p>0.05). H represents the variance of the ranks among the groups, approximately chi-square distributed with degrees of freedom 1 less than the number of groups (McDonald 2009). NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

3.3.4 Nematodes

An identification of nematode genus with numbers estimated per gram of dry soil was included in the commercial report for all the 20 farm sites in both 2008 and 2009.

3.3.4.1 Nematode diversity

Of the 51 taxa groups the fungal feeding *Ditylenchus* and *Aphelenchus* were the most populous identified (Table 3.17). The most common bacteria feeding colonists were *Panagrolaimus, Cephalobus* and *Heterocephalobus*; the most common predator was *Clarkus*; the most common plant associated genus was *Filenchus*; the most common omnivore was *Eudorylaimus*; and the most common plant-feeding genus identified was *Paratylenchus* (Table 3.17).

Table 3.17: Total populations (mean number per gram at 0-5 cm) of nematode taxa in cropped and non-cropped soil with the nominated feeding group and c-p value.

Feeding Group	cp value	Taxon	2008 Cropped	2008 Non-cropped	2009 Cropped	2009 Non-cropped
1	3	*Achromadora*	0.00075	0	0.00250	0.02800
1	2	*Acrobeles*	0.1195	0.5168	0.22030	0.13500
1	2	*Acrobeloides*	0.08925	0.06250	0.04200	0.07800
1	4	*Alaimus*	0	0	0.01925	0.00850
1	3	*Bastiana*	0	0.01500	0	0
1	1	*Caenorhabditis*	0.00923	0	0.07225	0.13450
1	2	*Cephalobus*	0.34570	0.38200	0.53630	0.12050
1	2	*Cervidellus*	0.07325	0.04050	0.05475	0.01500
1	2	*Chiloplacus (pointy)*	0.00825	0	0	0.00200
4	2	*Chiloplacus (stubby)*	0.02075	0	0.00075	0.00850
3	1	*Cuticularia*	0	0	0	0.01150
1	2	*Eucephalobus*	0.10600	0.02450	0.03575	0.06200
1	1	*Eumonhysteria*	0.05775	0.05000	0.10070	0.03450
1	1	*Geomonhystera*	0.01225	0.18300	0	0
1	2	*Heterocephalobus*	0.25650	0.64700	0.35050	0.13400
1	1	*Monhystera*	0.04975	0.01200	0.13900	0.25000
1	1	*Panagrolaimus*	0.85080	1.69200	0.77070	0.40500
1	2	*Plectus (lt)*	0.03200	0.11550	0.12400	0.07900
1	2	*Plectus (st)*	0.14870	0.17400	0.59000	0.11300
1	3	*Prismatolaimus*	0.04400	0.14500	0.28350	0.04600
1	1	*Rhabditis*	0.03000	0.03150	0.03050	0.02650
1	3	*Rhabdolaimus*	0.00075	0	0.00550	0
1	3	*Teratocephalus*	0	0	0	0.00550
2	4	*Tylencholaimellus*	0.01000	0	0.00950	0.01300
1	2	*Wilsonema*	0.1542	0.1915	0.24720	0.04500
6	5	*Aporcelaimellus*	0.00325	0	0.00525	0.05900
6	5	*Aporcelaimus*	0	0	0	0
6	5	*Discolaimus*	0.00175	0	0	0
2	4	*Epidorylaimus*	0.00425	0.03900	0.02125	0.10700
6	4	*Eudorylaimus*	0.10070	0.29150	0.17330	0.42550
6	4	*Mesodorylaimus*	0.00175	0	0	0
2	4	*Microdorylaimus*	0	0.01850	0.00700	0.04500
2	4	*Prodorylaimus*	0	0.02250	0.00050	0
2	4	*Thonus*	0.09450	0.02800	0.05475	0.05450
2	2	*Aphelenchoides*	0.7228	0.9935	1.32100	0.22200
2	2	*Aphelenchus*	1.0270	1.0930	0.4315	1.18050
3	2	*Aprutides*	0	0.0040	0	0
5	3	*Bitylenchus*	0	0.003	0.1178	0.00550
2	2	*Ditylenchus*	1.973	1.562	1.94900	0.28000
5	2	*Filenchus*	0.21100	0.19950	0.66050	0.07550
5	2	*Lelenchus*	0.03925	0	0.05650	0
5	2	*Tylenchulus*	0	0.003	0	0
5	3	*Merlinius*	0	0	0.00100	0
3	4	*Clarkus*	0.00950	0.01650	0.04425	0.12150
3	4	*Mylonchulus*	0	0.3888	0	0
4	4	*Coonmansus*	0	0.05550	0	0
4	2	*Gracilacus*	0	0	0	0.03
4	3	*Heliciotylenchus*	0.002750	0	0	0
4	3	*Hopolaimus*	0	0	0	0.00250
4	3	*Meloidogyne*	0	0	0.00175	0.00300
4	2	*Paratylenchus*	0.13630	0.00700	0.51720	0.06350
4	3	*Pratylenchus*	0.06250	0.00300	0.63020	0.03000

3.3.4.2 Nematode abundance and functional groups

In both years there was a significant reduction in omnivorous feeding nematodes (OF) in the lower productive cropped soil compared to the non-cropped reference soils (Table 3.18). In 2008 there were significantly more bacterial feeding nematodes (BF) in non-cropped reference soil than in lower productive ($P < 0.025$) and higher productive cropped soil ($P < 0.05$) (Table 3.18). In 2009 there were higher levels of predator nematodes in the non-cropped soil, more plant associated feeding nematodes in the higher productive cropped sites and less OF nematodes in the higher productive cropped sites compared to non-cropped soil (Table 3.18). In 2008 there was a significant ($P < 0.05$) reduction in OF nematodes in higher productive soils compared to lower productive cropped soils (Table 3.18). There were no significant differences in fungal feeding (FF) or plant feeding (PF) nematodes between soils in either 2008 or 2009.

Table 3.18: Functional groupings (proportions) of nematode populations. Information for feeding groups is based on numbers per gram of dry soil.

a Bacterial feeding nematodes

i 2008

H = 8.224; p = 0.016

CH			
CL	n.s.		
NC	*(NC>CH)	** (NC>CL)	
	CH	CL	NC

ii 2009

n.s

b Fungal feeding nematodes

i 2008

n.s.

ii 2009

n.s.

c Omnivorous feeding nematodes

i 2008

H = 8.492; p = 0.014

CH			
CL	*(CH>CL)		
NC	n.s.	** (NC>CL)	
	CH	CL	NC

ii 2009

H = 18.05; p < 0.001

CH			
CL	n.s.		
NC	***(NC>CH)	***(NC>CL)	
	CH	CL	NC

d Plant associated feeding nematodes

i 2008

n.s.

ii 2009

H = 9.576; p = 0.008

CH			
CL	*(CH>CL)		
NC	**(CH>NC)	n.s.	
	CH	CL	NC

e Plant feeding nematodes

i 2008

n.s.

ii 2009

n.s.

f Predator nematodes

i 2008

n.s.

ii 2009

H = 19.68; p<0.001

CH			
CL	n.s.		
NC	***(NC>CH)	**(NC>CL)	
	CH	CL	NC

For each parameter, overall ANOVA was carried out by using the non-parametric Kruskal-Wallis method and pairwise site comparisons by one-tailed Mann-Whitney. *p<0.05; **p<0.025; ***p<0.005. Letters in brackets refer to the sites. n.s., not significant (p>0.05). NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

3.3.4.3 General nematode indices

The nematode channel ratio (NCR) for both years was significantly lower in cropped soil compared to the non-cropped reference soils (Table 3.18). This difference was only small but could indicate a trend towards increased fungal feeding nematodes in cropping soil. There was a consistent increase in the percentage of cp-2 nematodes and decrease in cp-1 nematodes in cropped soils in both years (Figure 3.6). Other nematode indices were less consistent. Species richness (SR) was higher in higher producing cropped soil in 2008 but significantly higher in non-cropped soil in 2009 (Table 3.18). In both years SR was lowest in the low productive cropped soil. Only in 2009 the maturity index (MI) was higher in the non-cropped soil. In 2008 the Shannon-Weiner diversity index (H') was highest in higher productive cropped soil and in the lower productive cropped soils the dominance index (λ) was highest and the evenness index (J') lowest.

Table 3.19: Indices of the nematode faunae

Sites: Index	NC	CH	CL	l.s.d. ($P = 0.05$)
		2008		
SR	0.95 a[a]	1.13 b	0.87 a	0.107
H'	1.80 a	1.93 b	1.80 a	0.119
λ	0.23 a	0.20 a	0.33 b	0.037
NCR	0.57 a	0.41 b	0.36 b	0.060
J'	0.84 a	0.84 a	0.75 b	0.033
∑MI	1.91	2.07	1.96	n.s.
		2009		
SR	1.44 a	1.12 b	1.16 b	0.215
H'	2.12	2.00	1.90	n.s.
λ	0.16	0.17	0.21	n.s.
NCR	0.62 a	0.49 b	0.47 b	0.041
J'	0.86	0.84	0.81	n.s.
∑MI	2.42 a	2.04 b	2.13 b	0.248

[a] means followed by same letters are not significant as determined by GLM analysis, n.s., Not significant. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil. SR refers to species richness, H' Shannon-Weiner diversity index, λ refers to dominance index, NCR refers to nematode channel ratio, J' refers to evenness index and ∑MI refers to maturity index.

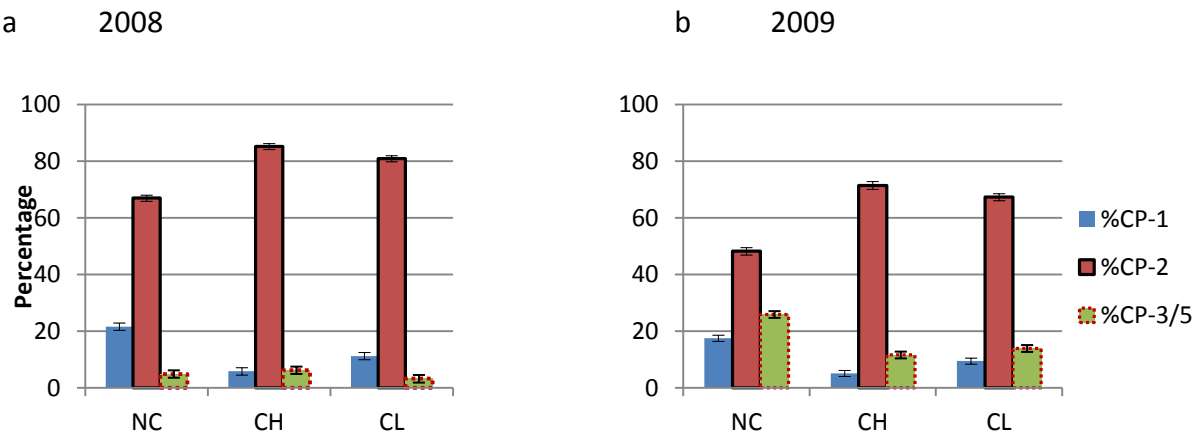


Figure 3.6: The percentage of nematodes in colonizer-persister (cp) groups of 1, 2 and 3 to 5. Vertical Bar indicates standard error. NC refers to non-cropped soil, CH Higher productive cropping soil and CL refers to lower productive cropping soil.

3.3.5 Correlation among soil biological, chemical and physical properties

The correlation of some microbial properties with certain abiotic, physical and chemical characteristics appears to indicate that soil C might be positively correlated to fungi biomass levels, omnivorous feeding nematodes and negatively correlated to bacterial feeding nematodes (Table 3.19). Total fungal biomass appeared to be positively correlated to soil strength, ground cover, soil C and nitrogen levels and the C: N ratio and negatively correlated to soil pH (Table 3.20). Ground cover that was significantly higher in natural grassland reference soil (Table 3.6) was significantly correlated with omnivorous feeding nematodes (OF) and fungal biomass (TF) as well as the ratios AB: TB and TF: TB in all soil (Table 3.20). Soil moisture appeared to be positively correlated to total nematodes but negatively correlated to TF: TB. Soil strength is negatively correlated with total nematodes but positively correlated to TF, TF: TB, AB: TB and AF: AB (Table 19).

Table 3.20: The correlation between selected microbial populations and ratios with certain physical and chemical soil properties (2009 data).

	Nematodes:						**Bacteria and Fungi**:			
	Total	BF	FF	OF	NCR	Cp-2 %	TF	TF:TB	AB: TB	AF: AB
Clay(%)	↑**	n.s.	n.s.	n.s.	n.s.	↑ *	n.s.	↓ **	n.s.	↓ *
Soil strength (kpa)	↓ *	n.s.	n.s.	↑*	n.s.	n.s.	↑ ***	↑ ***	↑ *	↑*
Field moisture (%)	↑ ***	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	↓ **	n.s.	n.s.
Ground cover (%)	n.s.	n.s.	n.s.	↑ ***	n.s.	n.s.	↑ **	↑*	↑*	n.s.
Total C (%)	n.s.	↓ *	n.s.	↑*	n.s.	↓ *	↑ ***	↑ **	n.s.	n.s.
Total N (%)	n.s.	n.s.	n.s.	↑*	n.s.	↓ *	↑ ***	↑ *	n.s.	n.s.
C:N	n.s.	↓ ***	↑*	n.s.	↓ *	n.s.	↑ *	↑ **	n.s.	↑ *
pH	↑ *	↑ *	↓*	n.s.	↑ *	n.s.	↓ *	↓ ***	n.s.	↓ *

[Significant levels (***) p< 0.0005; (**) p< 0.005; (*) p<0.05; n.s. = not significant, ↑ = increase, ↓ = decrease].BF refers to bacterial feeding nematodes, FF to fungal feeding nematodes, OF omnivorous feeding nematodes, NCR to nematode channel ratio, cp-2% to colonizer-persister group 2, TF to total fungal biomass, TB to total bacterial biomass, AF active fungal biomass and AB active bacterial biomass

Except for the Morgan P soil test in 2008 there was no significant correlation with the amount of microbial biomass and the availability of P (Table 3.21).

Table 3.21: The correlation between microbial biomass and available phosphorous

Phosphorous Test	2008	2009
Morgan	↑**	n.s.
Bray 1	n.s.	n.s.
Colwell	n.s.	n.s.
Bray 2	n.s.	n.s.

[Significant levels (***) p< 0.0005; (**) p< 0.005; (*) p<0.05; n.s. = not significant, ↑ = increase]

3.3.6 Crop management

3.3.6.1 Length of time since last cultivation

The ratio of total C %, total N %, and SMB C and Cp-2 nematodes in cropped soil compared to their reference sites was found to be significantly positively correlated to the length of time since the last cultivation (Figure 3.7). The wide variation of points along the lines of best fit indicate that, while the lack of cultivation is a positive influence on these properties, it is not the only factor involved. On some individual farms the ratio of some properties was

greater than 1 indicating that the cropped soil had higher values than their reference non-cropped soil (Figure 3.7).

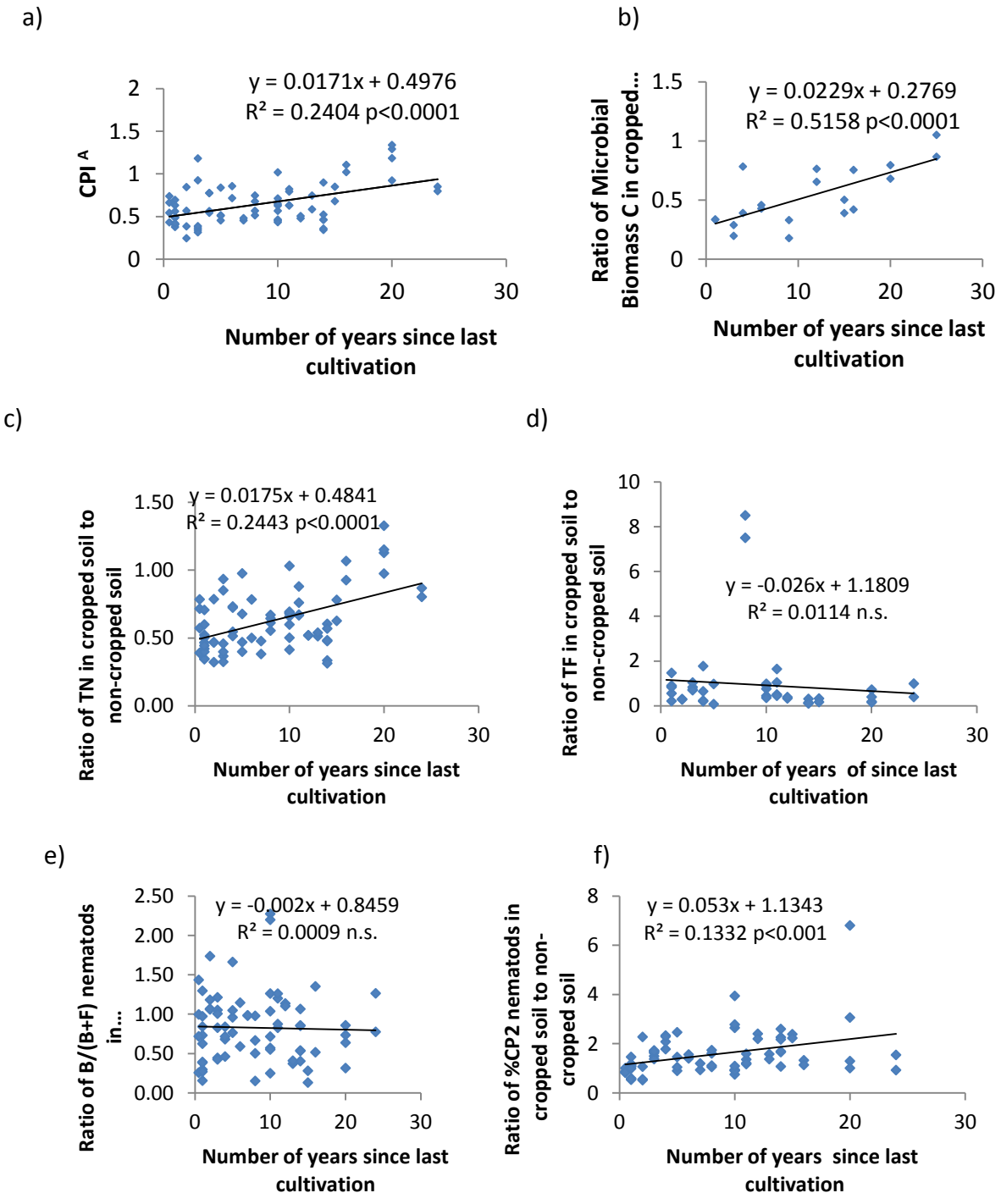


Figure 3.7: The correlation between the ratios of several biological properties in cropped soil to non-cropped soil with the number years that cultivation had not occurred based on; (A) % of total C; (B) SMB C; (C) % of total N; (D) total fungal biomass; (E) the ratio of Bacterial Feeding Nematodes to Fungal Feeding Nematodes; (F) % of CP2 Nematodes. [A]CPI = carbon pool index = Total C sample/Total C reference (Blair *et al.*, 1995)

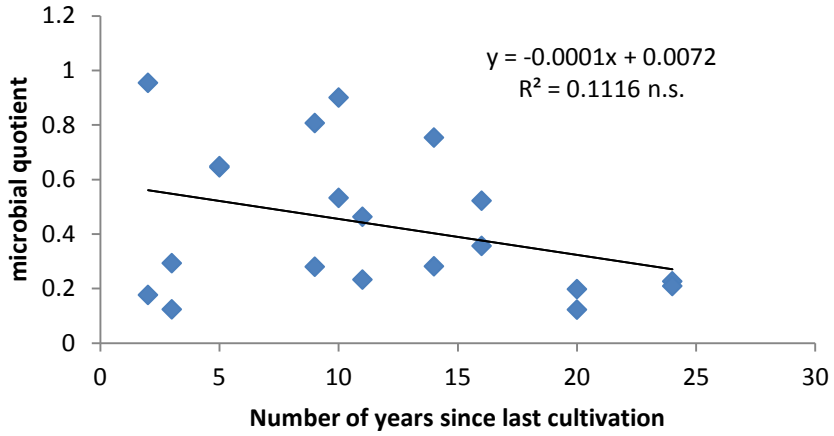


Figure 3.8: The correlation between the microbial quotients (ratio of microbial biomass to total C %) with the number of years since the last cultivation.

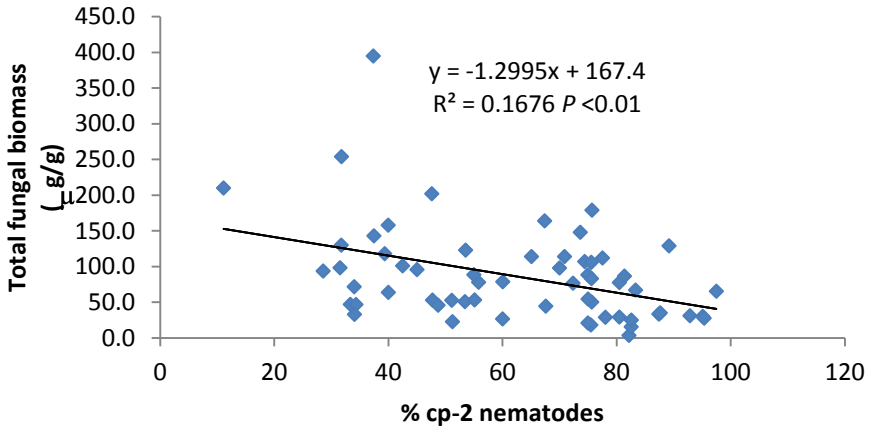


Figure 3.9: The correlation between the percentage of cp-2 nematodes and the total fungi for 2009 data

While there was no significant difference with the length of no-till on the microbial quotient (Figure 3.8) there was a significant decline in TFB as the % of cp-2 nematodes increased (Figure 3.9).

3.3.6.2 Crop rotations

There was a positive relationship between total C % and SMB C with the number of winter crops grown in the last five years (Table 3.22). There was a positive relationship between cropped soils that had a greater diversity of crop types with total C % and total N % but not SMB C. While total C % was significantly correlated with the number of oilseed crops, SMB C was significantly correlated with the number of cereals but negatively correlated with the

number of oilseeds grown in the last five years (Table 3.22). On cropping soils compared to non-cropped soils there was a highly significant increase in total fungal biomass, if oilseeds were part of the rotation (Table 3.22).

Table 3.22: Correlations between frequency of crop types and the ratio of selected chemical and microbial soil properties in cropped soil compared to their reference non-cropped soil.

Crops in last 5 years:	TC: NCTC	TN:NCTN	TF:NCTF	SMB C:NCSMB C	B/(B+F): NC B/(B+F)	%CP2:NC%CP2
winter crops	↑*	n.s.	n.s.	↑	n.s.	n.s.
crop types	↑*	↑*	n.s.	n.s.	n.s.	n.s.
cereals	n.s.	n.s.	↓*	↑*	n.s.	n.s.
oilseeds	↑*	↑*	↑***	↓*	n.s.	↑**
pulses	n.s.	n.s.	n.s.	n.s.	↑*	n.s.
summer crops	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
pastures	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
winter fallows	n.s.	n.s.	n.s.	↓*	n.s.	n.s.

* p-value < 0.01 ** p-value < 0.001 ***p-value < 0.0001 n.s. not significant ↑positive correlation ↓negative correlation, NC prefix refers to non cropped adjacent natural grassland soil

3.3.6.3 Impact of pesticides

There is no evidence that the number of applications of glyphosate (the most common knockdown herbicide used) glean®, ally ® (commonly used residual herbicides), insecticides or fungicides on cropped soil were detrimental to total C %, total N, SMB C, total fungal biomass or to the NCR nematode ratio. The use of insecticides is positively correlated with total C % and total N % and fungicides with total N % and SMB C (Table 3.23).

Table 3.23: The interaction of the number of times certain pesticides were applied on soil in the previous 12 months and some selected chemical and microbial properties

	Glyphosate	Glean®	Ally®	Artificial Insecticides	Fungicides
total C	n.s.	n.s.	n.s.	↑ *	n.s.
total N	n.s.	n.s.	n.s.	↑ *	↑ *
SMB C	n.s.	n.s.	n.s.	n.s.	↑*
TF	n.s.	n.s.	n.s.	n.s.	n.s.
NCR	n.s.	n.s.	n.s.	n.s.	n.s.

* p-value < 0.01 ** p-value < 0.001 ***p-value < 0.0001 n.s. not significant ↑positive correlation ↓negative correlation

3.3.6.4 Impact of artificial fertilizers

When combining all cropping sites from both surveys together and comparing that to their non-cropped reference site it appears that there was a significant increase in the ratio of total C in cropping soils compared to non-cropped reference soils (total C: NC total C) in those cropping soils that had higher rates (above 41 kg N/ha) of N fertilizer applied (Table 3.24). This amount of N fertilizer also had positive influences on the ratio of total N % in cropping soils to non-cropped soils (TN: NCTN). There was no significant advantage of using higher rates of N fertiliser to influence SMB C and it even may have a detrimental effect at rates below 40 kg N/ha (Table 3.24). There was no evidence of significant effects on these properties from the application of P fertilizer (data not shown).

Table 3.24: Effects of nitrogen and phosphorus fertilizer applied during the previous 12 months

a. Total C: NC total C

H = 9.7 p=0.008

0 (38)			
1-40 (32)	n.s.		
41-76 (10)	*41-76>0	*41-76>1-40	
Kg N/ha	0 (38)	1-40 (32)	41-76 (10)

b. TN: NC TN

H = 10.26 p=0.006

0 (38)			
1-40 (32)	n.s.		
41-76 (10)	*41-76>0	*41-76>1-40	
Kg N/ha	0 (38)	1-40 (32)	41-76 (10)

c. SMB C: NC SMB C

H = 6.3 p=0.043

0 (38)			
1-40 (32)	*0>1-40		
41-76 (10)	n.s.	*41-76>1-40	
Kg N/ha	0 (38)	1-40 (32)	41-76 (10)

For each parameter, overall ANOVA is carried out by the non-parametric Kruskal-Wallis method and pairwise site comparisons by one-tailed Mann-Whitney. *$P < 0.05$; Letters in brackets refer to the sample size. ns, not significant (p>0.05). H represents the variance of the ranks among the groups, approximately chi-square distributed with degrees of freedom 1 less than the number of groups (McDonald 2009).

Similarly the application of N fertilizer at rates above 40 kg N/ha appears to be significantly related to an approximate 17% increase in *Ditylenchus* and 4 % increase in *Cephalobus* nematode populations. The application of P fertilizer at rates above 10 kg P/ha was associated with a significant approximate 3% increase in *Cephalobus* population (Table 3.25).

Table 3.25: The change in abundance of two common genera of nematodes identified, as well as being present in non-cropped soil, as affected by applications of N and P fertilizer

	Ditylenchus (%) change	*Cephalabus* (%) change
	Effect of N fertilizer	
0 kg N/ha	1.15 (2.15) a	0.667 (0.95) a
1-40 kg N/ha	1.45 (3.26) a	0.799 (1.2) a
40-76 kg/ha	2.89 (16.99) b	1.613 (4.024) b
l.s.d. (*P* = 0.05)	0.76	0.43
	Effect of P fertilizer	
0 kg P/ha	1.164 (2.2)	0.672 (0.96) a
1-10 kg P/ha	1.500 (3.5)	0.706 (2.03) a
10-30 kg P/ha	1.985 (6.3)	1.27 (2.56) b
l.s.d. (*P* = 0.05)	ns	0.48

Data represents means of ln(x + 1) transformed percentage change in nematode numbers per gram of soil compared to adjacent uncultivated natural grassland soil. Actual percentage change in nematode abundance is shown in parenthesis.

3.4 DISCUSSION

3.4.1 Soil variability

Soil has dynamic properties that are a result of the interaction of both fundamental and changeable climatic, abiotic, physical, chemical and biological properties as well as being influenced by human management practices. Soil texture is a relatively stable fundamental soil property that can influence soil infiltration, moisture retention, (Mendham, O'Connell and Grove 2002) total N % (Dalal and Mayer 1987) and availability of other nutrients which may have a significant impact on microbial communities (Lauber *et al.* 2008). The variability in soil texture would therefore have some influence over certain chemical and biological soil properties. In this study there were no significant differences in texture between cropped and non-cropped soils (Table 3.6).

3.4.2 Impact of no-till cropping on soil physical characteristics

Management practices such as herbicide spraying of plants during fallow periods may have the ability to effect soil moisture levels, its penetration resistance and there might a change in the percentage that the ground is covered by plant residues. While the control of fallow plants are considered necessary in CW NSW for maximum production of the following crop (Hunt and Kirkegaard *et al*. 2011) there are few studies undertaken to identify the resultant changes that may effect on soil ecological and biological processes within this region. Plant residues are important substrates for microbial decomposition as they are eventually replaced in soil organic matter by microbial biomass (Ahmed and Oades 1984). While the control of weeds may result in an increase in stored soil moisture (Hunt *et al.* 1987) which may reduce soil strength (Whitbread 1996) it may also reduce the amount of residue cover which may then increase soil strength as soil strength and cover are positively correlated (Whitbread 1996). If soil strength, as measured by penetration resistance, increases to levels of above 2500 Kpa then plant roots can become restricted (Taylor, Roberson and Parker 1966). In this study no-till cropping, as practiced by the people in this survey, appeared to be having a positive influence of reducing soil penetration resistance (Table 3.6 and Figure 3.4), probably due to the strong correlation with soil moisture (Table 3.9). While reduced penetration resistance is strongly correlated with soil moisture, the results of this survey indicate that, unlike soil moisture, it is also correlated with decreasing levels of total fungal biomass, omnivorous feeding nematodes and related to the decrease in the ratio of total fungal biomass to total bacterial biomass; active bacterial biomass to total bacterial biomass; and active fungal biomass to active bacterial biomass (Table 3.20). The aim of the farmers in this survey was to maximise the moisture content of their summer fallows but these results may be possibly indicating that soil microbes are reacting in unpredicted ways to the related change in soil strength soil strength and/or moisture levels. More research is needed to clarify if these apparent correlations are an actual cause and effect or correlated to another parameter.

In both years the non-cropped soils had significantly more ground cover than cropped soils and there was a positive correlation between increased ground cover and increased soil C and N (Table 3.9) and similar positive correlations of biological effects as mentioned for soil

strength (Table 3.20). These results are only indicators at this stage and more detailed research is needed to determine the real drivers of change.

In 2009 there was a significant increase in soil moisture in cropping soils compared to non-cropped soils. Interestingly in 2008, on average, there was not a significant increase in soil moisture in the upper zone of cropping soils compared to their reference soils. This may be a seasonal result as the mean number of days since a rain event of 20 mm or more was 69.3 days in 2008 and only 24.7 days in 2009. Possibly due to the longer dry period before soil measurements were taken in 2008 the cropping paddocks on average did not have significant more moisture stored in the soil than non-cropped soils. In 2009 however fallow management of the surveyed farms meant that more moisture was stored in the soil than in non-cropped soils (Table 3.6). It is unclear at this stage what the role of higher ground cover had contributed to higher soil moisture levels (Table 3.6). Soil moisture levels while being related to clay content (Table 3.8) were also positively correlated to the population of flagellates, amoebae and ciliate protozoa (Table 3.14), as well as nematode populations but it had a negative correlation with the ratio of total fungal biomass to total bacterial biomass (Table 3.20). This implies that soils with higher moisture levels were more bacterial dominant and had higher protozoan and nematode populations. Soils with less moisture tended to be more fungal dominant. This finding is in contradiction of some research that has found that relative fungal biomass increases with an increase in soil moisture (Frey, Elliot and Paustian 1999). It is thought that fungal chitinous walls make fungi less resistant and resilient to soil moisture changes (Holland and Coleman 1987) but that soil bacteria that inhabit soil pore spaces can survive soil moisture stress better than fungi that inhibit the exterior of pore spaces (Frey, Elliot and Paustian 1999). This highlights the complex nature of how soil microbes have evolved to adapt and survive in varying soil moisture conditions.

Comparing higher and lower productive cropped sites, the only abiotic significant difference was less ground cover in the 2009 survey on lower productive cropped soils compared to higher productive areas (Table 3.6) which may be a direct consequence of lower crop productivity. Despite the reduction in the amount of cover there was not a significant decrease in soil fungal biomass between higher and lower productive cropping areas (Table 3.13) as might be expected as soil cover is highly correlated to total soil fungi biomass (Table 3.20). This suggests that the present level of residues may not be enough to reverse the

reduction in fungal biomass in cropping soils (Figure 3.6) or that other factors are also involved.

3.4.3 Impact of cropping on soil chemical characteristics

3.4.3.1 Soil carbon

Measured soil total C comprises both organic and inorganic C. Estimation of the percentage of organic C in total C ranges from world averages of 58% (Guo and Gifford 2002) to 67% (Batjes 1996). Organic residues derived from animals, plants and microbes are the sources of organic matter (OM) in soils of which organic C and N are important constituents. The labile C fraction of organic matter comprises the plant and animal residues that have very short turn-over times, ranging from weeks to a few years. The more recalcitrant (non-labile) C fraction comprises microbial metabolites, humic acids, and highly lignified materials which may remain in the soil for longer periods of time such as several years or even decades (Theis and Grossman 2006). It has been proposed that the major influences on the accumulation of C is governed by the differences in photosynthetic gain by plants and ecosystem respiratory losses due to plants, animals and microbes (Chapin III, Woodwell *et al.* 2006). It has been suggested that cultivation is one of the major causes of C losses in the soil, as the buried residues are more rapidly decomposed due to greater contact with soil, nutrients and soil decomposers (Beare *et al.* 1992). Rapid decreases in soil C have been noted soon after the first cultivation (Haines and Uren 1990; Whitbread 1996) and some research has demonstrated that it is slowly improved with the adoption of no-till (Gupta *et al.* 1994) but some studies have shown that there is still a large reduction in soil C in some Australian no-till systems (Bell *et al.* 2006).

This present study found that total C was on average 35-50% lower in no-till cropped soil compared to the reference soils (Table 3.8). These results are similar to those found by meta analysis of world wide soil C by Guo and Gifford (2002) which found that there were 97 recorded observations of reduction in soil C of approximately 59% when pasture is converted to cropping. Australian research in Queensland comparing cultivation to no-till found an increase in soil C in no-till soils (Dalal 1989) but when no-till was compared to native grasslands there was a 55% reduction in organic C (Bell *et al.* 2006). Research by Whitbread (1996) found that cropping soils that included cultivation practices, compared to non-cropped reference soils in various parts of northern NSW had reduced total C by 75 %

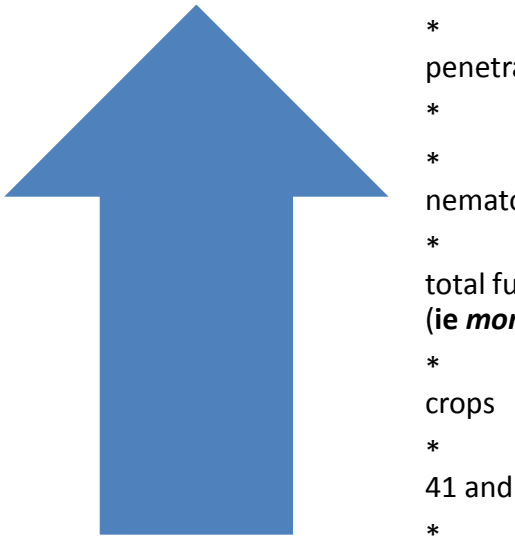
with labile C being more negatively impacted than the non-labile fraction. In this study the correlation between the reduction of total C (compared to the reference soil) and the number of years since the last cultivation shows a significant positive trend ($P < 0.0001$) (Figure 3.7a) resulting in an increase of total C the longer the period of no-till. The number of years that these paddocks went without cultivation (except for sowing with a tyne or disc sowing implement) ranged from 1 to 25 years. The wide variation of points around the line of best fit indicates that soil C reduction is also influenced by factors other than cultivation. A small number of individual sites had higher levels of C compared to their reference soil (shown with values greater than 1). This possibly indicates that, at least in a small number of some cases, it is possible to practice no-till agriculture in CW NSW and at least maintain natural soil C levels or even improve upon them. As this is such a small data set further research is needed to clarify this.

The practices in this survey that appear to be associated with the storage of C in the soil is an increased length of time since the last cultivation, combined with a higher frequency of winter crops, a greater diversity of crop types, in particular oilseed crops (Table 3.22) as well as the use of N fertilizer at rates of 40-75 kg N/ha (Table 3.24) and the use of insecticides (Table 3.23). As these are correlations they may not necessarily be the cause of increased C so further study is needed to clarify this. This trend however may confirm other studies that have demonstrated increased soil organic C levels with no-till (especially combined with standing stubble compared to stubble burning, stubble mulching or stubble cultivation) (Slattery and Surapaneni 2002) as well as the positive influence of the application of fertilizer N on a regular basis (Paustian, Parton and Persson 1991) and other practices that promote biomass production (Lal 2004). It might be argued that the use of insecticides may promote biomass production.

There was little difference in total C between high and low crop productive sites on the soils surveyed except for 2009 (Table 3.8). The difference between 2008 and 2009 in the ability to store C is unclear but may be related to the drier period before the 2008 testing as already mentioned. If this is the case the higher crop productivity seems to be related to the soils ability to store more soil C but only in appropriate years. The increase in soil C appears to be correlated with an increase in omnivorous nematodes and total fungal biomass as well as an increase in the ratio of total fungal biomass to total bacterial biomass

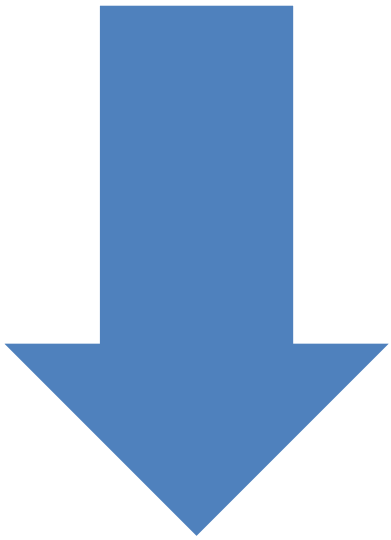
(Table 3.20). It appears to be negatively correlated with the number of bacterial feeding nematodes and the group of nematodes ranked cp_2 (relatively early colonizers) (Table 3.20). As stated previously it is also positively correlated with soil hardness and percentage of ground cover (Table 3.9). These results are summarised in Table 3.26.

Table 3.26: Summary of positive and negative correlations with soil carbon levels



Positive correlations with soil carbon are:

* Increasing ground cover and soil penetration resistance.
* Increasing total nitrogen percentage
* higher number of omnivorous nematodes
* total fungal biomass and higher ratio of total fungal biomass to total bacterial biomass (**ie *more fungal dominant soil***)
* Higher frequency and diversity of winter crops
* Moderate use of N fertiliser (between 41 and 75 kg/ha)
* Insecticide use



Negative correlations with soil carbon are:

* higher numbers of bacterial feeding nematodes
* higher numbers of cp2 nematodes (relatively early colonizing nematodes)
* Cultivation of the soil

3.4.3.2 Total nitrogen

N is one of the major nutrients required for annual crop production. When in adequate supply it supports both yield and protein in wheat. While there are various forms of N in soil (organic and inorganic), it has been suggested that between 90% and 98% of N in A horizon soils is in the organic matter (Ajwa and Tabatabai 1994; Bremmer 1965). In this survey total N was highly correlated to total C in both 2008 and 2009 (Table 3.9). Like total

C, total N was significantly reduced in both cropping sites compared to non-cropped soil in both years (Table 3.8). The decline in N content of soils has been noted elsewhere when land is put into crop production and is thought to further steadily decline over time unless N fertilizer is used (Schneiner and Brown 1938; Stevenson 1982). In this survey although there was an average decline in total N in cropping soil, the ratio of total N in cropped soils to their uncropped reference soils tended to increase with the length of time since the last cultivation (Figure 3.8). This may be due to fertilizer being added to the cropping soils but 22.5% of survey soils did not have fertilizer applied within the last five years (Table 3.3). While soil inorganic N is commonly less than 2% of TN of surface soils it appears in these surveys that N in the form of NH_4 rather than nitrate is lower in cropping soils with a significant 50% and 42% ammonium reduction in the 2008 and 2009 surveys respectively (Table 3.8).

There was not a significant difference in total or ammonium N between productive areas of cropped soil (Table 3.8). This indicates that the level of total N or ammonium levels in the soil in the top 0-5 cm at sowing time may not be related to past levels of biomass production. As total N was highly correlated with total C it had similar correlations with total C except in 2008 total N was correlated with the percentage of clay in the soil (Table 3.9) and it was not correlated with the population size of bacterial feeding nematodes as total C was (Table 3.20). As for total C, total N was positively correlated with the use of artificial insecticides and fungicides (Table 3.23). While the cause of this is unknown but could be related these products allowing for better legume growth. Fungicides in these surveys were mainly used on chickpea crops for control of Ascochyta Blight, a serious chickpea disease in Australia (Moore *et al.* 2011) and chickpeas have been known to have a positive effect on soil N due to N_2 fixation in certain circumstances (Schwenke *et al.* 1998) as well as pulse crops having less N losses (Drinkwater, Wagoner and Sarrantonio 1998) due to N not as likely to volatilise or be leached as N can be if applied as inorganic fertilizer (Jensen and Hauggard-Nielsen 2003). The use of chickpeas in the rotation was not correlated to total N so more in depth research is needed to clarify these interactions.

Changes in C: N ratio are negatively correlated to bacterial feeding nematodes and NCR but positively correlated to fungal feeding nematodes, total fungal biomass as well as to the ratios of total fungal biomass to total bacterial biomass and active fungal biomass to active

bacterial biomass (Table 3.20). This confirms with other research that the fungal community is correlated with the soil C: N ratio (Allison *et al.* 2007; Christensen 1989; Frey *et al.* 2004; Lauber *et al.* 2008).

3.4.3.3 Soil pH

Differences in soil-forming factors, the season of the year, cropping practices, vegetation, and the soil horizon sampled as well as water content at sampling time can all influence the soil pH level (Thompson and Troeh 1978). Vegetation has a complex influence on soil pH. To maintain electrolyte balance in both soil and plants, living plants release either excess hydroxyl or bicarbonate ions if the soil solution they absorb contains more anions (such as nitrates) or excess H^+ in the presence of more cation absorption (such as ammonium) (Thompson and Troeh 1978). The decomposition of plant material can often release unequal amounts of organic acids and bases (Thompson and Troeh 1978). Therefore a change in vegetation, fertilizer types, crop yields and rates of decomposition could all have different effects on soil pH and it is considered that increased acidity is a potential risk when uncropped land is converted to high production annual cropping (Glendinning 2000). There was no evidence of differences in soil pH between areas of higher and lower crop production in this survey (Table 3.8) which indicates that the current levels of crop production are not having a detrimental effect on soil pH. Increased moisture without plant growth, as can occur during crop fallow periods, can increase the risk of leaching bases and therefore lowering pH over a period of time.

In these surveys fallowing using herbicides to conserve moisture is a common practice on cropping soil. Despite some individual sites having higher levels of moisture in cropping compared to the reference soils, the mean soil moisture was only significant in the 2009 survey but this did not appear to decrease soil pH levels (Table 3.8). The higher productive sites had a higher pH compared to the non-cropped reference soils in 2008 (Table 3.8) and there is little evidence to suggest that cropping frequency, the current levels of crop productivity or increased levels in soil moisture are having an acidifying effect on the soils of CW NSW. This is in contrast to other research that has shown levels of soil pH to be lower under no-till cropping (Dalal and Mayer 1987). Soil pH was positively correlated with total nematode and in particular bacterial feeding nematodes and the NCR ratio but negatively correlated with fungal feeding nematodes, total fungal biomass as well as the ratios of the

total fungal biomass to total bacterial biomass and active fungal biomass to active bacterial biomass (Table 3.20). This supports other research that higher soil pH supports bacterial dominated communities (Lauber *et al.* 2008) and lower soil pH supports fungal dominated communities (Frey, Elliot and Paustian 1999).

3.4.3.3 Other nutrients

Nutrient mining is a risk associated with annual cropping as large amounts of nutrients are removed in grain. While most farmers surveyed either use artificial or organic fertilizers, about 22.5 % did not use fertilizers to replace nutrients (Table 3.3). Despite lower total N, these surveys did not determine that either soil nitrate or phosphorous, which are important cropping nutrients, were significantly lower in cropping soils compared to uncropped soil. Of the other nutrients only Fe and Mn availability in both surveys were significantly reduced (by a factor of 21-39%) in cropping soils compared to their reference soils (Table 3.8). Small amounts of Fe and Mn are important for plant photosynthesis and other biochemical reactions (Humphries *et al.*, 2007; Romheld and Nikolic, 2007). The availability of these nutrients can be linked to soil pH levels. Fe is less available in calcareous and heavily limed soils as increasing levels of soil pH up to 7.4 decreases solubility of total inorganic Fe but it can become more available in the presence of organic compounds (Romheld and Nikolic 2007). The alkaline effect of nitrate fertilizer if used can also reduce Fe availability (Romheld and Nikolic 2007). As with Fe, the availability of Mn in soils is affected by soil pH levels, decreasing as pH increased (Humphries, Stangoulis and Graham 2007).

There is little evidence that crop productivity areas differ in levels of available Fe (Table 3.8). Levels of potassium (K), sulphate and manganese were lower in cropping soils only in the 2009 survey indicating that reduced levels of these nutrients may be of some influence on crop productivity but only in the soils surveyed in 2009.

3.4.4 Impact of cropping on soil biological characteristics

3.4.4.1 Soil microbial population

The soil microbial population is the driving mechanism behind plant nutrient recycling, retention and release (Figure 3.11). The measurement of SMB C as one method to estimate the size of this part of the living component of soil organic matter (Jenkinson and Ladd 1981) has been considered to be sensitive to certain management practices (Dilly 2006), so

it is often used to compare soils of natural ecosystems with those that have been modified under agriculture (Sparling 1997). These surveys have indicated that cropping had reduced mean SMB C in both 2008 and 2009 by approximately 58% and 45% respectively (Table 3.10) possibly indicating long term soil ecological change due to cropping. These results support other studies that have detected a reduction in microbial biomass following cultivation of the soil (Buckley and Schmidt 2001; Salinas-Garcia *et al.* 2002; Wardle 1995) and in particular are similar to trends observed in the central Darling Downs area of southern Queensland which found a 30-50% reduction of SMB C on their no-till cropping soils compared to natural grasslands (Bell *et al.* 2006). There may be many causes for this decline besides disturbance of the soil from past cultivation. In this research it appears, just as for soil C and total N, SMB C might also recover with time from initial reductions from the effects of cultivation (Figure 3.8). This confirms other research that has shown that SMB C can be increased after conversion to no-tillage (Stromberger, Shah and Westfall 2007). The period of time to go without cultivation so that SMB C fully recovers is unclear from these surveys but it appears that a full recovery may take at least 15 to 20 years (Figure 3.8). Other factors that might be related to increases in SMB C in cropping soils over time might be the inclusion of more winter crops and less winter fallows but with more cereals than oilseeds (Table 3.22). The use of fungicides appears to be associated with higher SMB C (Table 3.23) but small amounts of artificial N fertilizer (less than 40 kg N/ha) appears to have a negative effect on SMB C with the optimum being between 40-75kg N/ha (Table 3.24). More research is needed to confirm this.

Some studies have suggested a strong link between SMB C and soil fertility (Sparling 1997), in particular N (Manning *et al.* 2008b) and the amount of SMB C could be an early indicator of long term changes in soil fertility (Wardle *et al.* 1999). In these surveys it appears that non-cropped soils in general have higher SMB C combined with higher total N and higher ammonium N but not necessarily nitrate levels (Table 3.8). This partly confirms other research that indicates lower ammonium levels in some cropped soils but higher nitrate levels in tilled soils compared to native (Bruns *et al.* 1999). While higher SMB C and total N indicates that non-cropped soil has the potential for greater future N mineralisation and cropping soils have higher levels of available N at the time of testing the measurement of soil nitrate levels are complicated by additions of fertilizer N on some cropping soils as well

as the different responses due to soil textures as more total N is lost from the sand-size rather than the silt and clay-size fractions of the soil (Dalal and Mayer 1987). However it might be concluded from this research that while higher SMB C is associated with areas of higher total N and ammonium in non-cropped soils indicating higher retention of soil N, it is not necessarily associated with more plant-available nitrates in the soil at the time of testing.

There is also little evidence to suggest that higher levels of microbial biomass are linked to higher levels of available phosphorous (Table 3.21). The exception is that there is an indication that in 2008 there was a significant positive relationship with the amount of available soluble P, as determined by the Morgan test, and SMB C. These results confirm other studies that have shown that higher levels of microbial biomass does not always relate to greater amounts of 'plant-available' nutrients (Sparling 1997). One possible explanation for this is that the microbial pool can become a sink for plant available nutrients and in some cases it has been shown that as SMB C increases, soil fertility in terms of immediate plant available nutrients actually decreases (Grayston *et al.* 2001). It is thought that the release of nutrients from the microbial biomass pool is linked to the level of microbial predation (Bardgett *et al.* 1999; Clarholm 2005; Ingham *et al.* 1985; Tu *et al.* 2003; Yeates and Pattison 2006). In this study however it appears that the level of the protozoan and total nematode population had little effect on total N (Tables 3.13 and 3.19) and there were not significant rises in available N or P with increasing levels of either protozoa or nematodes (data not shown). A possible model depicting the movement of nutrient between pools is summarized in Figure 3.11. This demonstrates that while the soil microbial biomass pool can be increased it does not necessarily affect plant growth unless plants can access the mineralized nutrient pool. If there are any breaks in the nutrient flow between different pools then the mineralized pool would not be increased. While more research is needed to clarify why there is not increasing available nutrients with increasing SMB C or to the current level of predators, one possible solution worth investigating is that does the predator level need to be at a higher critical threshold to influence mineralization.

A disadvantage of the SIR method as used in these studies is that it only estimates the microbial biomass that responds to easily degradable compounds (Beck *et al.* 1997), so any microbial biomass that degrades more recalcitrant material may not be included. Despite

that disadvantage, the microbial quotient, is considered a good indicator of soil exploitation and has been shown to decrease if the microbial C pools decline at a faster rate than the total organic matter (Sparling 1997). In these surveys the microbial quotient was significantly higher in non-cropped soils than in cropped soil in 2008, but only significantly higher than the higher productive cropped soils in 2009 (Table 3.11). This indicates that cropping in CW NSW could be exploiting biological C in some areas, especially in higher productive situations. Pankhurst *et al.* (2002) found both the microbial biomass and microbial quotient in the top 0-5 cm increased after changing from cultivation to no-till but the surveys in this study showed no significant correlation between the microbial quotient and the length of no-till (Figure 3.9).

3.4.4.3 Microbial structure

While it appears that the microbial population may recover with time from past cultivation it has been found by other research there is some evidence that the structural change in microbial communities is not necessarily reversed by ceasing cultivation (Buckley and Schmidt 2001). In particular recently tilled soils may have a lower diversity in the autotrophic ammonia oxidizing microbial community (Bruns *et al.* 1999) as well as the structural changes in the denitrifying microbial community (Buckley and Schmidt 2001). One possible indicator of microbial structural change is the ratio of respiration to microbial biomass (qCO_2) (Isam, Hutchinson and Reber 1996). This indicator did not demonstrate structural microbial change in these surveys. There were other indicators, however, that did indicate that there was microbial structural change due to cropping.

In this study there was a significant (P <0.001) rise in the ratio of bacterial biomass to total C in cropped soil (a mean increase of 39% in higher productive and 69% in lower productive cropped soil compared to non-cropped soil). While this study has not investigated the reason why the total C content of no-till soils appear to have a greater proportion of bacterial biomass, it is known that no-till inputs, such as herbicides, become substrates for bacterial microbes (Brusse *et al.* 2001). This indicates that while microbial biomass C may be depleted at a faster rate than that of total C especially in the higher crop production areas, the bacterial biomass portion is not.

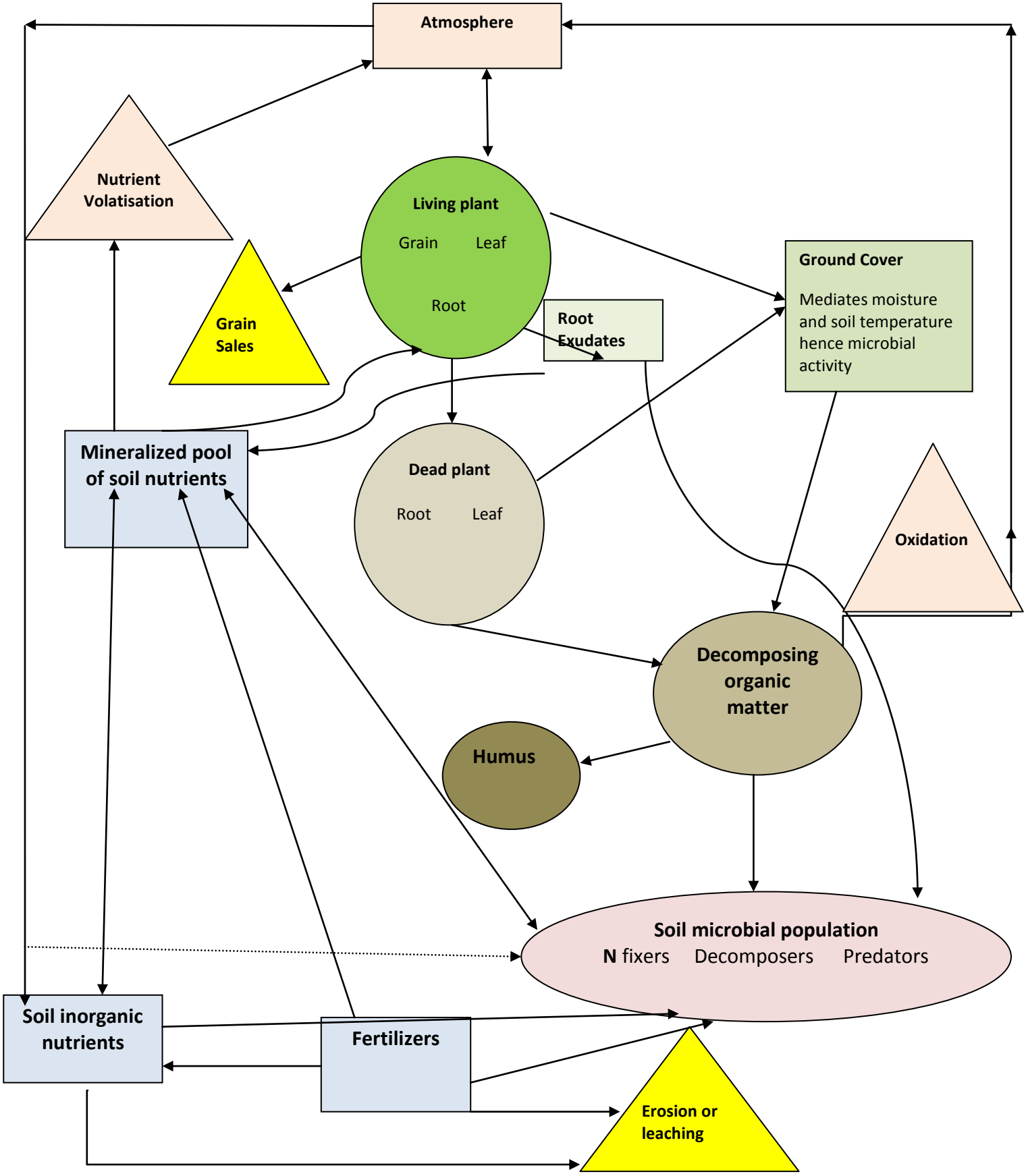


Figure 3.11: Possible model of the nutrient movement between pools in the no-till farming situation. Arrows indicate direction of flow.

A further indication of structural change is that while total bacterial biomass remained unchanged there was a 49% mean reduction in total fungal biomass levels in cropping soils in the larger sample size of 2009 (Table 3.13). As well as being a food source for predators, soil fungi, like bacteria, decompose organic residues and are involved in nutrient cycling and the formation of soil organic matter which develops and maintains soil structure (Stahl, Parkin and Christensen 1999). The results from this survey suggest that the both total and active fungal biomass could be negatively affected by cropping (Table 3.13). Unlike soil C and microbial biomass, soil fungal biomass does not appear to be positively responding to the length of time without cultivation (Figure 3.8). This appears to contradict research that suggests that soil fungi respond favourably to no-till compared to conventional tillage (Doran 1980a; Frey, Elliot and Paustian 1999; Stahl, Parkin and Christensen 1999). However other research has suggested that once fungal biomass is lost due to certain agricultural activities such as cultivation a halt to those activities does not necessarily increase fungal levels past certain stabilizing levels for many decades (van der Wal *et al.* 2006).

Fungal to bacterial biomass ratios give an indication of the dominance of fungi in soils and can be used as an indication of which group is most active in the decomposition of plant material (Beare *et al.* 1990). This survey has shown that even though the grassland non-cropped reference soils were highly bacterial dominated as indicated by TF:TB ratios less than 0.5 (Table 3.16) the ratio has been further significantly reduced in both productive and less productive cropping soils compared to these non-cropped reference soils in 2009 (Table 3.16). The activity of fungal biomass appears to favour the lower productive cropping soil which may indicate that the type of fungal activity is not positively contributing to plant productivity (Table 3.16) whether this is due to the presence of disease fungi is beyond this study but is noted that fungi may survive in more extreme environments than does bacteria as they are physiologically more capable of growing under drier conditions than are most bacteria (Beare *et al.* 1992; Frey, Elliot and Paustian 1999). Some research has found a negative correlation between F: B and qCO_2 (Blagodatskaya and Anderson 1998; Sakamoto and Oba 1994) which may indicate that fungi are more efficient than bacteria in their utilization of substrate (Six *et al.* 2006).

The reasons behind the decrease of both fungal biomass and in the ratio F: B in the cropped soils may be due to either soil property changes or the use of cropping inputs that are

detrimental to soil fungi. Substrate quality in cropped soils may have lower C: N ratio of organic matter and higher proportions of easily decomposable substrates (carbohydrates from annual crop residues), easily decomposed by bacteria, compared to more "woody" perennial species found in non-cropped soils that may increase fungal decomposition (van der Wal *et al.* 2006). Soil pH differences may also affect the ratio of fungi to bacteria in soils. In these surveys the fungal biomass levels were negatively correlated with soil pH (Table 3.20). This confirms other research that has shown that soil fungal growth is very responsive to lower soil pH values (Rousk, Brookesand Bath 2009).

A change in predator numbers may also influence the ratio of fungal to bacterial biomass. Predators of bacteria and fungi can reduce the prey population but predator populations normally decline following the reduction of prey keeping a balance between prey and predator numbers (Ingham *et al.* 1986). There does appear to be a consistent decrease in the Nematode Channel Ratio [NCR =B/ (B+F)] and an increase of cp_2 nematodes in cropped soil with a significant (P = 0.01) negative correlation with total fungal biomass (Figure 3.9). The drop in NCR indicates a proportional increase in fungal feeding compared to bacterial feeding nematodes. The cp-2 nematodes that include both bacterial and fungal feeding nematodes can withstand longer, harsher periods in both food-rich as well as food-poor conditions whereas cp-1 nematodes are mostly bacterial feeding, quick responsive nematodes with a short generation time that respond very quickly to food-rich conditions (Bongers and Bongers 1998). It is possible therefore that the decrease in fungal biomass in cropped soil might be related to the structural changes in the predator population with predator populations surviving for longer periods after the prey levels have decreased. This situation might result in a higher grazing pressure on the fungal biomass by these predators. Other causes of fungal decline might be caused by bacterial inhibition of fungi (Rosenzweig and Stotzky 1979). Bacterial biomass does not appear to be reduced with the reduction of microbial biomass in these cropping soils. This may indicate that the bacterial population is out competing fungal biomass. Knockdown herbicides were used by 95% of farmers surveyed (Table 3.3) and it has been stated that the use of these products can create higher available substrate levels for use by bacteria and actinomycetes but not fungi populations (Roslycky 1982). Research has shown that herbicides can have detrimental effects on soil microbial populations such as glyphosate on ectomycorrhizal fungi at least in the short time

of 2-6 months (Chakravarty and Chatarpaul 1990) and on entomopathogenic fungi (soil surface fungi which can protect plants from spider mite attack) (Morjan, Pedigo and Lewis 2002). If the effects of glyphosate are only temporary it is possible that the fungal biomass has not fully recovered at the time of sampling in these surveys, especially if there are several sprays throughout the fallow period. Chakravarty and Chatarpaul (1990) found no effect on soil microbial populations 9 months after 3.23 kg/ha of glyphosate were applied on forest soils. Soil texture may also influence the persistence level of glyphosate. Eberbach and Douglas (1983) found that glyphosate persisted longer in a sandy loam soil (at least for 120 days), however there does not appear to be a significant correlation with the use of glyphosate and other commonly used herbicides and the level of total fungal biomass in cropping soils (Table 3.23).

3.4.4.4 Soil nematodes

Nematodes can not just provide information on their link to crop production losses but also how they are involved in nutrient mineralisation, control of microbe populations including plant pathogens and the transfer of microbial-based energy and nutrients to other parts of the soil food web (Ingham 1994b). An in-depth study of the nematode population to identification to genus level was done in this study so it could be used as a possible indicator of the effect of no-till farming on overall diversity and function of microbial populations. In agroecosystems the three critical determinations of nematode diversity are soil texture, soil moisture and the availability of suitable foods (Yeates and Bongers 1999). Tillage has also been found to change the dominance of particular types of nematodes (Yeates and Boag 2004). No-till farming has the potential to change the amount of soil moisture, type of plant remains but little is known of the overall effect on nematode populations and their diversity in cropping soils of CW NSW. The results of the surveys in this study have shown that nematode properties vary between sites but there were 4 consistent trends that emerged after two years of surveying. In cropping soils in general there was a drop in NCR (Table 3.20) and an increase in cp-2% nematodes compared to non-cropped reference soils. In lower productive cropping soils compared to their reference soils there was a significant drop in omnivorous feeding nematodes (Table 3.18) as well there was a decrease in overall diversity as described by the species richness (Table 3.19). Lower values of NCR indicate that there are proportionally more fungal feeding nematodes in cropped soil despite the lower levels of fungal biomass. In general, soil features that favoured increasing total

nematode populations were soils with higher clay content, moisture and soil pH but lower soil strength (Table 3.20). In particular bacterial feeding nematodes seemed to be correlated with increased soil pH but lower total C and lower C: N ratios. Fungal feeding nematodes seemed to be correlated to lowering soil pH and increasing levels of C: N ratios. Omnivorous feeding nematodes seemed to be correlated with increasing soil strength and ground cover, total C and total N. NCR with decreasing C: N ratios and rising soil pH and cp-2% was correlated with increasing clay content but decreasing total C and N (Table 3.20). Nematodes classed as cp-2 seemed to be positively correlated ($P < 0.001$) with the length of time of no-till without cultivation (Figure 3.8) but there was a correlation between cultivation and NCR (Figure 3.8). As the percentage of nematodes increased in the cp-2 group it appeared that it had a negative effect on total fungal biomass (Figure 3.10). Crop rotations seem to be having a minor effect on nematode diversity as increasing pulse crops seems to increase NCR (bacterial feeding dominant) and increasing oil seed crops seem to favour cp-2 nematodes (Table 3.22).

The level of crop production does seem to be correlated to nematode population or diversity except that in 2008 there were less omnivorous feeding nematodes and in 2009 less plant associated nematodes in lower productive cropping soils compared to higher cropped soil (Table 3.18). There was an indication in 2008 that overall diversity as defined by SR, H', λ and J' was decreased in lower productive soils (Table 3.19) but this trend was not repeated in the 2009 survey.

3.4.4.5 Soil protozoa

Soil protozoa are an important part of the sustained biological fertility of soil as they can release significant quantities of mineral N into the soil environment (Williamson and Wardle 2007). Their grazing is often synchronized with plant uptake of available N which reduces losses of soil nutrients (Bonkowski *et al.* 2000). Despite what looks like a large reduction in protozoan numbers in the small sample size survey of 2008 (Figure 3.6) there were no consistent trends or significant differences in protozoan levels between the soil sites (Table 3.13) mainly due to wide variability (Table 3.12). There was also no significant correlation between total C or N, nitrates or ammonium with amoeba, flagellate or ciliate populations (Table 3.14). However the overall mean levels of amoebae and flagellates were low reaching a mean of 2 602 and 3 613 respectively in non-cropped soil (Table 3.12) compared

to levels found in other studies where un-cropped agricultural soil which have been shown to have 30 000 amoebae, 7 000 flagellates and 155 ciliates per gram of dry soil with even higher levels in soils with actively growing plants (Darbyshire & Greaves 1967). In this study all protozoan types were significantly positively correlated to soil moisture levels. Flagellates and ciliates were significantly positively correlated with active bacteria levels and amoebae are significantly positively correlated to total bacterial levels (Table 3.14). This confirms other research that has found that protozoan levels vary with moisture levels and prey numbers (Ingham 1994a). There was not a significant correlation between size of the population of protozoa and soil texture or pH (Table 3.14) which might be expected for other groups of microorganisms (Roper and Ophel-Keller 1997). Whether the low protozoan levels are a natural feature of CW NSW soils in general or are a result of other influences has not been identified in this research.

3.5 CONCLUSION

The surveys during 2008 and 2009 examined the top 0-5 cm of no-till cropping soils in CW NSW demonstrated that, when compared to non-cropped soil, there were some significant changes in some biological and chemical soil properties. In particular there was an overall reduction in total C and N, microbial and fungal biomass by at least 35%, 42%, 45% and 49% respectively. There was however an increase in the population of fungal feeding nematodes when compared to uncultivated natural grassland soil. While there may be many reasons for these soil changes where grasslands have been converted to cropping, the loss of total C, total N and microbial biomass is apparent but they appear to be positively responding to the length of no-till. It appears that it is the fungal rather than bacterial portion of microbial biomass that is linked to increases in soil C but it appears fungal biomass unlike soil C is not responding positively to no-till in CW NSW. The reasons for this are unclear in these studies but there are indicators that need further investigation. These include the possible link to reduced percentage of soil cover, soil pH changes, bacterial biomass interactions and the structural changes of prey species in cropped soil such as the percentage increase in cp2 nematodes. Other factors that may be involved are possible changes in substrate quantity or quality or some other management practices and/or agricultural inputs that are detrimental to soil fungi.

There is little consistent evidence obtained in these baseline studies to determine the general drivers of differences in crop production in these soils. There is some evidence to suggest that current higher levels of crop production are linked to higher population levels of soil microbial properties but these studies suggest the possibility that increased diversity of nematodes is positively related to higher crop production. The major consistent difference between areas of crop productivity is that there are higher levels of active fungal biomass and higher ratios of active fungi to both active and total bacterial biomass in low productive cropped areas compared to higher productive areas. Why fungal levels are more active in lower productive sites and whether this is detrimental to plant growth needs further investigation.

The reasons for reduced fungal biomass levels in no-till cropped soils and lower diversity of nematodes in lower productive soil needs further investigation but it has been shown that in the cropping soils of CW NSW total soil C, N and microbial biomass has a positive correlation with the length of time of no-till farming. Management practices that include long periods without cultivation, diverse crop rotations, increased cropping frequency and moderate use of fertilizer as well as increases in the percentage of ground cover may help overcome some of the negative effects of cropping natural grasslands.

The issues identified in this chapter have shown that no-till cropping has produced some changes in physical, chemical and biological soil properties within the soils of CW NSW. Some of these changes may be corrected with time but others appear to be more permanent. The application of amendments may help rectify some of these changes so a more detailed comparison of amendments in terms of chemical, physical and biological soil properties is needed to assess potential benefits.

CHAPTER 4
EFFECTS OF SOIL AMENDMENTS ON CHEMICAL, BIOLOGICAL AND PHYSICAL SOIL PROPERTIES

4.1 INTRODUCTION

Healthy soils are considered to have chemical, biological and physical characteristics that promote long-term plant production. It has been identified in chapter 3 that dry land cropping in CW NSW has generally decreased some important soil properties compared to adjacent non-cropped soil. This includes a decline in soil C and SMB C (especially soil fungal biomass). While the survey indicated that soil C and SMB C may increase with longer periods of no-till it appears that soil fungal biomass may not. The results of a reduction in soil C and SMB C in no-till cropping soils are similar to those found in research on no-till agricultural soils in southern Queensland (Bell *et al.* 2006). The cause of this decline may be related to reduced soil cover in cropping soils (Chapter 3) which then may affect the level of cycling of plant material which in turn influences the level of soil biota. The reduction in soil C and microbial biomass may also be caused by other yet unidentified stresses caused by certain agricultural management practices.

It is generally understood that organic matter is fundamental to sustainable agriculture as it supports diverse biological communities which in turn support many soil functions such as nutrient supply (Lal 2004) and stabilisation of soil structure (Allison 1973) which are important factors in the commercial production of annual crops. The decomposition of organic matter by soil micro-organisms and the resultant benefit to crop production relies on a set of complex interactions that relate not only to the quantity and quality of organic matter but also on abiotic factors such as moisture, temperature (Fauci and Dick 1994; Guidi *et al.* 1988), soil characteristics such as clay content, aggregate size (Gupta and Roper 2010), soil pH (Rousk, Brookes and Bath 2009), nutrient availability especially soil phosphorous (Strickland *et al.* 2010) and nitrogen (Manning *et al.* 2008b), the plant species present, the related plant biomass and root exudates (Manning *et al.* 2008a) as well as the presence of microbial species and predators (Yeates 2003). It is believed that these multitudes of interacting factors create a complex system of cause and effect that make specific desired

outcomes very unpredictable (Yeates and Pattison 2006). While the certain outcomes may be unpredictable it is assumed that in any ecological complex system the more diverse systems are likely to maintain their function in the face of natural or man-made disturbances.

Soil organic amendments such as compost and manure were frequently used on agricultural land before the introduction of inorganic high grade fertilizers. The investigation of the benefits of crop mulches have a long history (Adams 1966) while amendments such as biochar and zeolite have gained more recent attention (Lehmann 2008; Pierzynski and Gehl 2005). It is hypothesised that there may be a role for these soil amendments in stubble retained controlled traffic no-till agricultural systems to repair the damage to the biological component of the agricultural soil ecosystem and their use may maintain or enhance soil biota diversity and/or crop production in a typical clay soil of CW NSW that does not rely on fertilizers for annual crop production.

This chapter reports the results of a field trial on Vertosol soil at Coonamble NSW to compare the effectiveness of these surface applied soil amendments in improving key soil properties that are considered important in the production of annual crops. The trial was conducted from May 2008 until November 2009. The site layout was maintained after 2009 where it was managed in with the rest of the paddock where wheat was grown in 2010. Yield data was collected from each plot in November 2010.

The aim of this trial is to investigate whether the additions of surface applied organic amendments have any significant influence on general soil and biological properties and crop yields in a no-till farming situation.

4.2 MATERIALS AND METHODS

4.2.1 Site description

4.2.1.1 Location

The research trial was located on a commercial no-till paddock at “Magomadine” surrounding Magometon (a small basalt outcrop) which is located 23 km East of Coonamble on the Tooraweenah Road in the CW NSW (Figure 4.1). The paddock has similar altitude to Coonamble which approximately 180 metres with latitude 30.98°S, longitude 148.38°E

(2009). This site was chosen as representative and typical of Vertosol soil that is one of the main soil types that are important for no-till cropping in CW NSW (Figure 4.2).

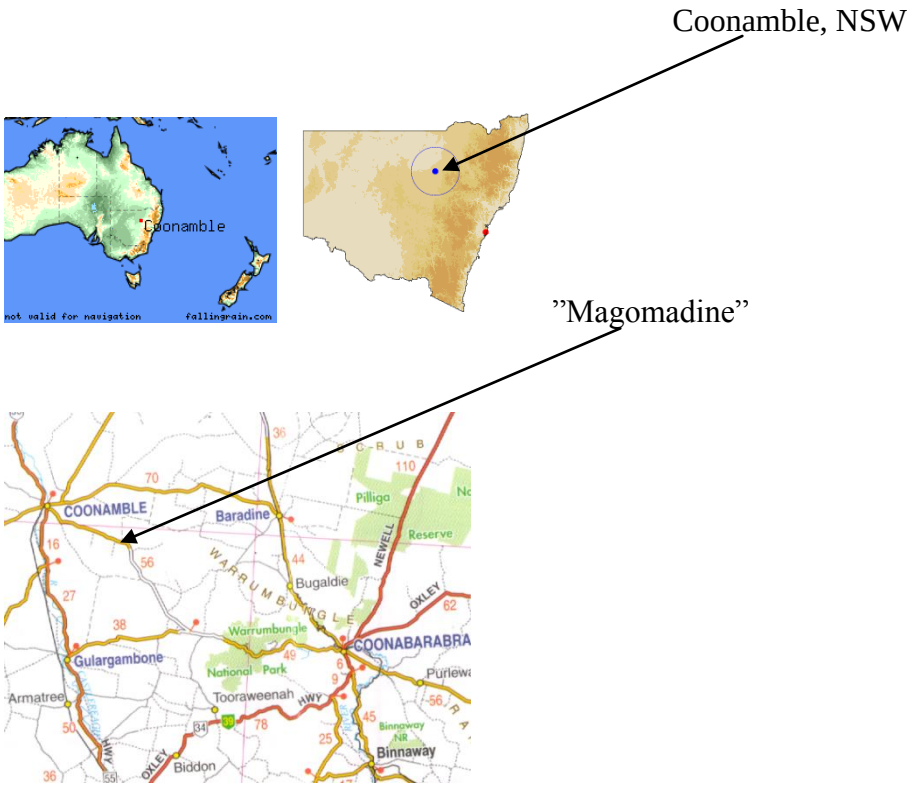


Figure 4.1: Locality maps of Australia, Coonamble in NSW and trial site on "Magomadine" property approximately 23 km East of Coonamble.

4.2.1.2 Climate

The Coonamble district has a temperate climate and a mean annual rainfall of 503mm with the regional average pan evaporation being 2000 mm (2009). The highest mean monthly average rainfall is 60.4 mm (January) which also has highest average monthly pan evaporation of 300mm (Figure 4.3). The lowest mean average rainfall occurs in both August and September (32.2 mm). The highest recorded annual rainfall was 1129 mm in 1950 and the highest monthly recorded rainfall was 294.4 mm (January 1984) (Figure 4.3). Variability in monthly cumulative rainfall varied considerably between 2008 and 2010 (Figure 4.4), the time period of the field trial.

The Mean minimum air temperature in winter (July) is 3.6°C, and mean maximum air temperature in summer (January) is 34.9°C (Figure 4.5).

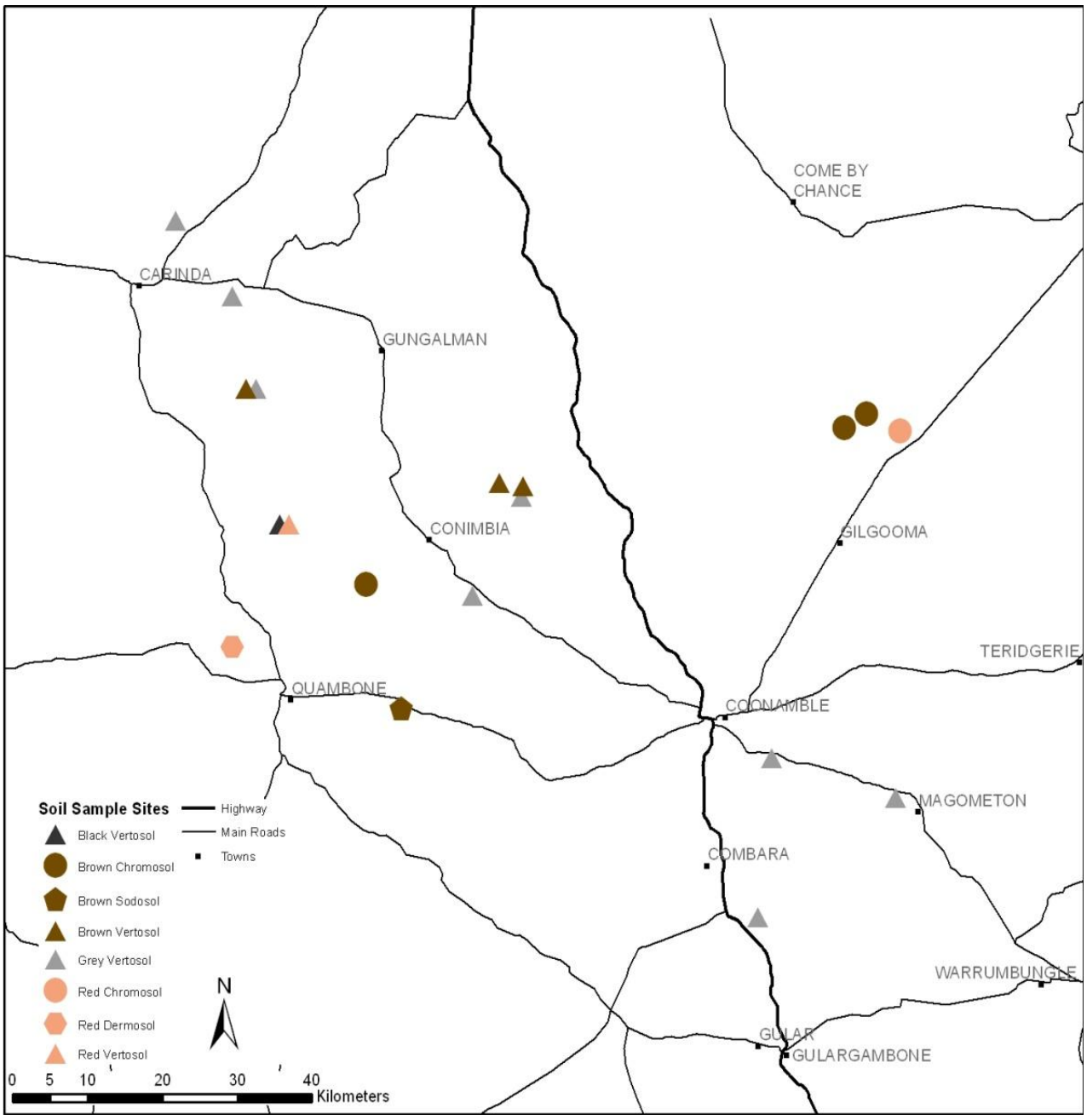


Figure 4.2: Soil map showing diversity of soil types around Coonamble. Source: Daniels, Manning and Pearce (2002)

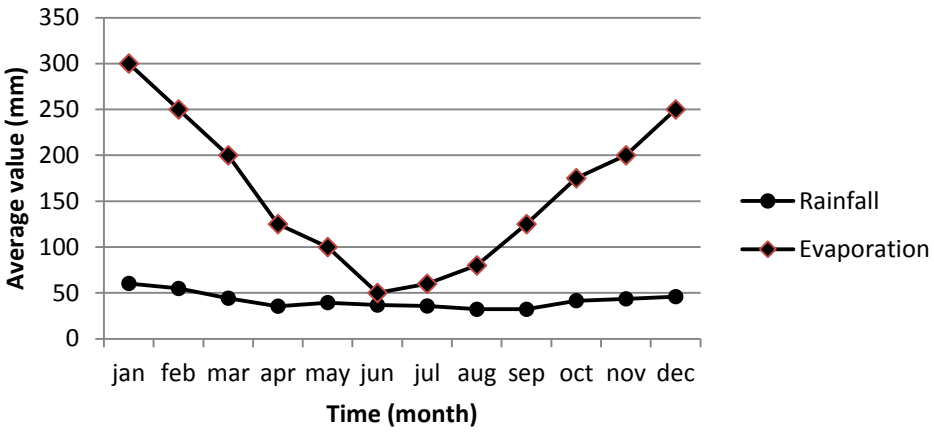


Figure 4.3: Long term average monthly rainfall (1878-2009) for Coonamble (23 km from "Magomadine") and district pan monthly evaporation (average of 10 years 1975-2009). Source: Australian Government (2009)

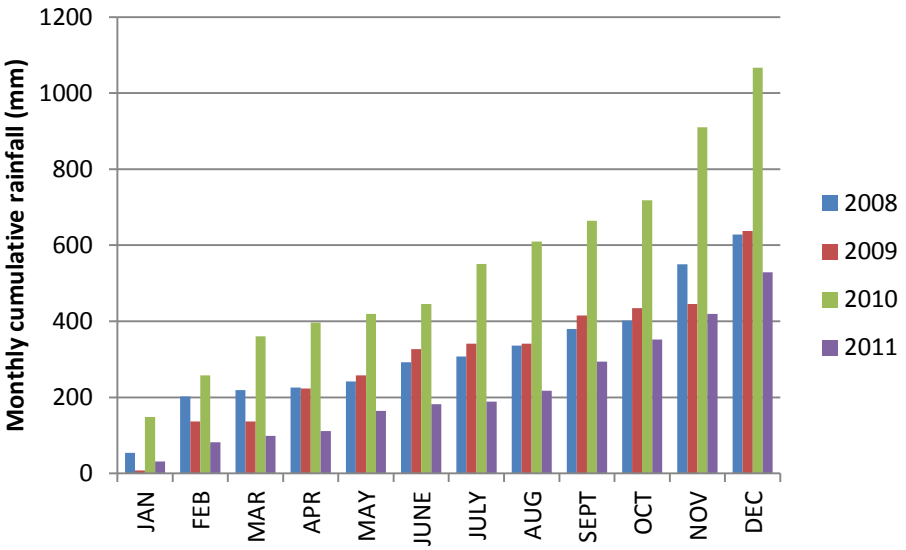


Figure 4.4: Cumulative monthly rainfall on "Magomadine", Coonamble for 2008, 2009, 2010 and 2011.

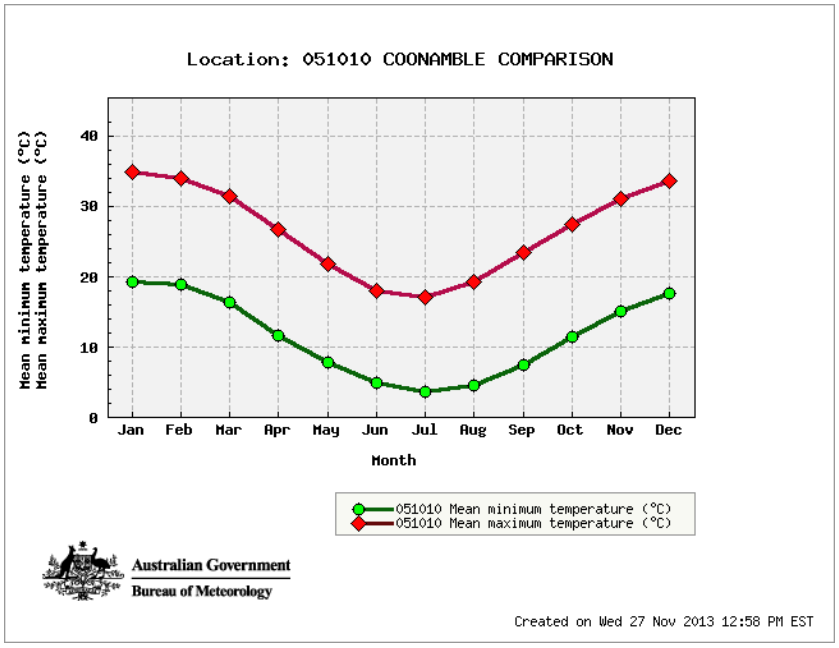


Figure 4.5: Long term average monthly maximum and minimum temperature (1878-2009) for Coonamble (23 km from "Magomadine") Source: Australian Government(2009)

4.2.1.3 Land Use

The Hill paddock on "Magomadine" was used as the site for the field trial. It was first cropped in 1997 after a long period of grazing. The first cultivations were a disc and blade plough to remove Myall suckers and from then on the paddock has been under a no-till system comprising herbicide sprays to control weeds and crops sown using a "Ground Hound" no-till tyne planter.

The winter crops planted in this paddock have been wheat (1997, 1998, 1999, 2001, 2004, 2006 and 2008), chickpeas (2000 and 2005), canola (2003) and linseed (2007). These crops are normally planted from May to June and harvested around November. During 2002 the planted canola crop was terminated in July due to lack of rain. The main herbicide used to control weeds between crops is glyphosate®, with simazine® and balance® used on chickpeas post sowing but pre emergent. Synthetic pyrethroids insecticides have been used to control Helicoverpa insects in the chickpea and linseed crops. Fungicides are normally sprayed on chickpeas to control Ascochyta blight. In 2008 fungicides were used for the first time on wheat to control stripe rust. There had been an application of 30kg/ha sulphate of ammonia fertilizer in 2002 and 30 kg/ha single superphosphate plus zinc in 2007. The

prominent weeds in this paddock are turnip weed, annual phalaris and ryegrass, wild oat and variegated thistle.

The trial site in this paddock is located in the north eastern corner of the paddock and has been under the same treatment as the rest of the paddock until May 2008. The soil on this site is Vertosol and Daniels, Manning and Pearce (2002) identified (during a regional soil characterisation) these soils as alkaline, sometimes sodic in the topsoil and strongly sodic and slightly saline in the subsoil. There is high electrical conductivity in the deeper subsoil due to the presence of gypsum and chloride. The plant available water capacity is moderate to high (170 mm).

4.2.2 Experimental design and layout

4.2.2.1 Design

In May 2008 the paddock was sown to Cunningham wheat using no-till farming methods. The experimental design of the field trial site was a randomized complete block in 4x4 split-plot arrangement. The organic amendments were applied to the surface of individual plots according to this experimental design (Figure 4.6). The types and rates of amendments are shown in Table 4.1.

Figure 4.6: Trial site in April 2009.

4.2.2.2 Layout

The trial had 16 treatments (Table 4.1) replicated three times. The treatments of straw (barley sourced locally), manure (feedlot sourced locally), compost (made on site from feedlot manure, hay and straw sourced locally) and control (no organic amendment) comprised the major plots of the split plot design. Each major plot was further subdivided into 4 sub plots to which each had either the equivalent of 6t/ha of biochar (wood based; sourced from Victoria), 6t/ha zeolite (100 micron powder sourced from Tenterfield NSW), both 3t/ha biochar and 3t/ha zeolite or no amendment (Table 4.2).

In June high numbers of volunteer barley emerged in the straw amended plots and the whole site was sprayed with the herbicide Atlantis® at 330 ml/ha. The herbicide had a detrimental effect on the trial killing most of the wheat plants so glyphosate was applied to remaining plants to terminate them. The site was then treated as a long fallow to investigate the possible influence of the amendments on soil properties without the interaction of plants. Wheat was harvested in the rest of the paddock. Amendments were reapplied on the field trial site in January 2009. The same amounts of organic amendments were applied. French white millet straw replaced the barley straw. The trial was then managed as per rest of the paddock (Table 4.3).

Table 4.1: Soil amendments and their application rate.

	Treatment	Application Rate
1	Straw	10 t/ha (dry weight)
2	Straw biochar	10 t/ha and 6t/ha (dry weight)
3	Straw zeolite	10 t/ha and 6t/ha (dry weight)
4	Straw biochar and zeolite	10 t/ha, 3t/ha and 3t/ha (dry weight)
5	Compost	10 t/ha (dry weight)
6	Compost biochar	10 t/ha and 6t/ha (dry weight)
7	Compost zeolite	10 t/ha and 6t/ha (dry weight)
8	Compost biochar and zeolite	10 t/ha, 3t/ha and 3t/ha (dry weight)
9	Manure	10 t/ha (dry weight)
10	Manure biochar	10 t/ha and 6t/ha (dry weight)
11	Manure zeolite	10 t/ha and 6t/ha (dry weight)
12	Manure biochar and zeolite	10 t/ha, 3t/ha and 3t/ha (dry weight)
13	Control	
14	Biochar	6t/ha (dry weight)
15	Zeolite	6t/ha (dry weight)
16	Biochar and Zeolite	3t/ha and 3t/ha (dry weight)

Table 4.2: Field trial design

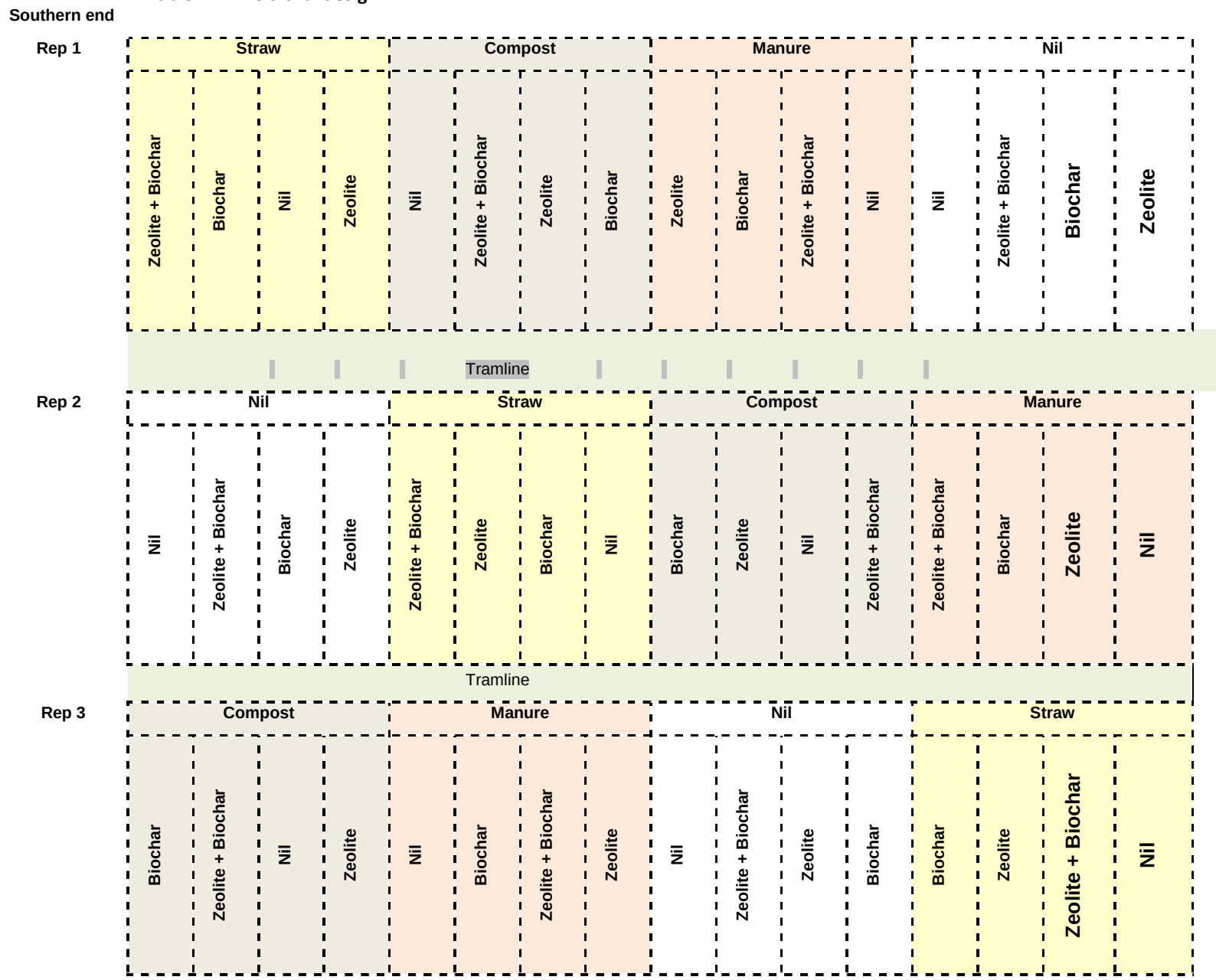


Table 4.3: Paddock and trial site management

Date	Treatment	Products used	Rate	Comments
20/12/2007	Fallow spray	Glyphosate Plus®	1.2 L/ha	Whole paddock
		Ally ®	7g/ha	Whole paddock
27/02/2007	Fallow spray	Glyphosate Plus®	1 L/ha	Whole paddock
		Zulu ®	1 L/ha	Whole paddock
7/04/2008	Fallow spray	Glyphosate Plus®	1 L/ha	Whole paddock
		Starane ®	350 ml/ha	Whole paddock
9/05/2008	Pre-sowing spray	Treflan ®	1.5 L/ha	Whole paddock
9/05/2008	Sowing	Cunningham wheat	27 kg/ha	Whole paddock
26/06/2008	In crop spray	Atlantis ®	330 ml/ha	Trial site only
25/07/2008	Termination of wheat in trial	Glyphosate Plus®	1.0 L/ha	Trial site only
26/08/2009	Fungicide spray	Tebuconazole Folicur®	150 ml/ha	Whole paddock
3/10/2009	Fungicide spray	Tebuconazole Folicur®	150 ml/ha	by plane to whole paddock
21/12/2008	Fallow spray	Glyphosate Plus®	1.5 L/ha	Whole paddock
		Estercide 680®	400 ml/ha	Whole paddock
12/01/2009	Amendments reapplied to plots			Trial site only
11/03/2009	Fallow spray	Glyphosate Plus®	1 L/ha	Whole paddock
		Estercide 680®	400 ml/ha	Whole paddock
24/03/2009	Fallow spray	Glyphosate Plus®	1.2 L/ha	Whole paddock
		Surpass ®	300 ml/ha	Whole paddock
10/05/2009	Pre-sowing spray	Glyphosate Plus®	1.2 L/ha	Whole paddock
		Treflan ®	1.5 L/ha	Whole paddock
11/05/2009	Sowing	Cunningham wheat	27 Kg/ha	Whole paddock
27/11/2009	Harvesting of Plots			Trial site only
5/5/2010	Sowing	Sunzell Wheat	27 kg/ha	Whole paddock
11/11/2010	Harvesting of Plots			Trial site only

4.2.3 Soil property assessment

In October 2008 and 2009 field moisture percentage for each plot was obtained by taking three measurements per plot using a MP406 Soil Moisture Sensor probe. Soil samples were collected from 0 - 5 cm, in the middle of each plot, close to plants but not so close as to disturb their growth. Properties that were analysed at UNE were aggregated stability, microbial respiration and biomass and various chemical properties. In 2009 additional soil samples from each plot were sent to Lismore Soil Foodweb laboratory for a commercial analysis of bacterial and fungal biomass and estimation of amoebae, flagellate, ciliate and nematode population sizes as well as the classification of nematodes to genus level.

4.2.3.1 Aggregate stability

Mean Weighted Diameter (MWD) of soil particles was used to give an indication of aggregate stability. This was undertaken at the physics laboratory at UNE, Armidale. Bags containing the soil samples were opened and placed in the green house to allow the soil to air dry. The soil was gently teased apart (avoiding smearing) to reduce large lumps down to about pea size. Dry weight of the soil was determined by placing about 25 g of soil into 100g tins, weighing combined soil and tin and lid and placing in a 105°C oven overnight. The soil and tins were then reweighed to calculate dry weight of the soil. Approximately 50 g of soil was placed into weighed plastic bottles, soil and bottle reweighed then the soil was placed into the top sieve of a mechanical shaker containing a stack of sieves from 8mm down to 0.125mm. Trialling was initially done to test the most appropriate setting and time for sieving. It was determined to use amplitude two for three minutes shaking. After three minutes the soil on each sieve was weighed. The MWD was calculated using the formulae

$$MWD = \sum_{i=1}^{n} x_i w_i$$

where x_i is the mean diameter of any particle size range of aggregates separated by sieving and w_i is the mass of the aggregates in that size range as a fraction of the total dry mass of the sample analysed.

4.2.3.2 Chemical properties

Soil analysis was completed at the Plant Nutrition Laboratory at UNE. The soil samples were air dried and subsamples were ground into less than 2mm as well as less than 0.5 mm particles. The following properties were then measured and recorded using these subsamples.

4.2.3.2.1 Soil pH

Ten grams of the less than 2mm subsamples were placed into plastic jars to which 50 ml of 0.01M $CaCl_2$ was added. The lid was screwed on and the bottle mechanically shaken for exactly one hour at 25°C. The soil pH was measured using a TPS 901-CP (conductivity –TDS-pH-mV).

4.2.3.2.2 Total nitrogen and carbon

Forty mg of soil sample was placed into 8x5mm tin capsules, and put into a mass spectrometer (Nitrogen/Carbon/Sulphur analyser Carlo Erba NA 1500) where total N and C were measured.

4.2.3.2.3 Colwell P

One gram of air-dried 2mm sieved soil was placed into 125 ml screw-top polythene bottles to which 100 ml of 0.5M $NaHCO_3$ at pH 8.5 was added. The lids were securely attached and the bottles were tumbled for 16 hours at 25°C on an end-over-end tumbler. After tumbling the solutions were filtered through Whatman No. 42 Filter papers into clean glass vials. To each 3ml filtered extract sample that was placed in a 12.5 ml plastic tube 3 ml of 0.5M sodium bicarbonate was added first and then 250µL of 1 M H_2SO_4 and mixed gently to allow effervescence to occur. This was repeated after 5 minutes. After signs that effervescence had abated 1 ml of mixed reagent was added and the tubes were placed in a spectrophotometer (Biochrom Libra S11) at 630nm to record the absorbance after 45 minutes. Regression curves for the standards of Absorbance (Y axis) vs concentration (X axis) were drawn up and the value of the unknowns was determined from the regression curve.

4.2.3.2.4 Exchangeable cation concentration

The exchangeable cations of Al, Ca, Mg, K and Na were analysed using 0.1M NH_4Cl at pH 7.0 extraction solution. Two grams of air-dried 2mm sieved soil was placed into centrifuged tubes to which 40 ml of the extraction solution was added. The stoppers were secured and tubes were mechanically shaken end-over-end at 25°C for one hour. The solutions were filtered through Whatman No 42 filter papers into class vials. The exchangeable cation concentrations of Al, Ca, Mg, K and Na of the filtered extract were determined using ARL 3560B ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectrometer).

The material and methods relating to assessment of microbial biomass and respiration, bacterial and fungal biomass, protozoa and nematodes are in Chapter 3.

4.2.4 Statistical analysis

All data was subjected to split plot analysis of variance. Residuals were examined for homogeneity and data was transformed when necessary. Treatment means were separated using 5% least significant difference (LSD) and those indicating significant differences were identified by different lower case letters. Tables of results for interactions between major and sub plot treatments were only presented if there were significant differences. Canonical variate analysis (CVA) was conducted where appropriate to determine linear combinations of the data variates that represent most of the variation between the groups of treatment data. Statistical analyses were performed using Genstat statistical software.

4.3 RESULTS

4.3.1 Changes in soil chemical properties

4.3.1.1 Soil carbon and nitrogen

Prior to the application of soil amendments in autumn 2008, total C levels in the field plot area averaged 1.1% compared to 2.2% in near by non-cropped soils (Table 6.1). While there appear to be very high fluctuations in total C in the non-cropped soil over a period of time, it is apparent that there was at least a 38% reduction in total C in cropped soils compared to neighbouring non-cropped soil (Table 4.4). No-till cropped soil dropped 0.1% in total C during the long fallow phase (Autumn 2008 to Autumn 2009) of the trial but regained 0.1% during the crop phase of the trial (Spring 2009) (Table 4.4).

Table 4.4: Baseline soil carbon data for field trial and adjacent non-cropped soil.

	Total C (%)			
	Autumn 2008	Spring 2008	Autumn 2009	Spring 2009
Non-cropped soil	2.2	n.a.	1.6	n.a.
Field trial soil with no amendments	1.1	1.0	1.0	1.1

n.a. not available

There was an increase in total C in the control soils between 2008 (long fallow) and 2009 (sown to wheat) but the surface application of straw, manure and compost in the field trial on this cropped soil significantly increased both soil C and N compared to the control after two years of application (Table 4.5). There was not a significant difference in soil C and N

between plots in the first year (2008). The C: N ratio was not significantly altered by the surface applications of these organic amendments in either year (Table 4.5).

Table 4.5: The effect of surface applied organic amendments on total C, total N (%) and C:N ratio in spring 2008 and 2009.

	Total C (%)		Total N (%)		C: N	
	2008	2009	2008	2009	2008	2009
Control [A]	1.0	1.2a[B]	0.1	0.09a	8.1	13.8
Straw	1.1	1.5b	0.1	0.12b	7.6	12.5
Manure	1.1	1.5b	0.1	0.11b	8.5	13.4
Compost	1.1	1.5b	0.1	0.11b	9.0	13.7
LSD	n.s.	0.188	n.s.	0.016	n.s.	n.s.
p-value		p =0.011		p=0.007		

[A] Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments.
[B] Means followed by the same letter within columns are not significantly different at p≤0.05.

The surface application of biochar, at a rate of 6 t/ha, significantly increased total C levels in both 2008 and 2009 (Table 4.6). In the spring of 2009 the total C levels in the biochar plots had increased to similar levels that were recorded in non-cropped soils in autumn 2009 (Tables 4.4 & 4.6). Halving the rate of biochar (applied with half rates of zeolite) did not appear to significantly raise total C levels in 2008 but there was a minor significant increase in 2009 (Table 4.6). The application of biochar and/or zeolite at full or half rates did not appear to significantly influence total N levels in the plots in either year. There was a significant increase in the C: N ratio in biochar plots in 2008 and in both full rates and half rate biochar & zeolite plots in 2009 (Table 4.6).

Table 4.6: The effect of surface applied biochar and zeolite amendment on total carbon, total nitrogen (%) and C: N ratio in spring of 2008 and 2009

	Total carbon (%)		Total nitrogen (%)		C:N	
	2008	2009	2008	2009	2008	2009
Control[A]	1.04a[A]	1.35a	0.13	0.11	8.0a	12.2a
Biochar	1.20b	1.63c	0.13	0.11	9.2b	15.3bc
Zeolite	0.98a	1.25a	0.13	0.10	7.6a	12.7a
B & Z	1.08a	1.46b	0.14	0.11	8.0a	13.4b
LSD	0.080	0.094	n.s.	n.s.	0.995	0.725
p-value	p<0.001	p<0.001			p=0.002	p<0.001

[A] Control plots are the sub plots that do not have biochar or zeolite amendments but may have straw, manure or compost treatments.
[B]Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.1.2 Soil phosphorous

Available soil P was significantly increased by the surface application of manure within the first year (Table 4.7). Available P appeared to be lower under straw and slightly higher under compost but these levels were not significantly different to those in the control plots in 2008.

Table 4.7: Effect of surface application of organic amendments on available P (µg g^{-1}).

	Colwell P (µg g^{-1})	
	2008	2009
Control[A]	72.0ab[B]	65.3a
Straw	63.7a	68.0a
Manure	107.5c	156.9c
Compost	86.9b	105.1b
LSD	16.13	18.19
p-value	p = 0.002	p < 0.001

[A] Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments.
[B] Means followed by the same letter within columns are not significantly different at p≤0.05.

In the second year available soil P was significantly higher in both manure and compost plots compared to the control plots. The addition of biochar and zeolite did not appear to significantly alter the availability of soil P in either year of testing (Table 4.8).

Table 4.8: Effect of surface application of organic amendments on available P (µg g^{-1}).

	Colwell P (µg g^{-1})	
	2008	2009
Control[A]	82.0	101.1
Biochar	85.6	102.2
Zeolite	80.3	92.6
B + Z	82.1	99.4
LSD	n.s.	n.s.

[A] Control plots are the sub plots that do not have biochar or zeolite amendments but may have straw, manure or compost treatments

4.3.1.3 Soil pH

The surface application of organic amendments did not significantly alter the soil pH in either 2008 or 2009 (Table 4.9).

Table 4.9: Effect of surface application of organic amendments on soil pH.

	Soil pH	
	2008	2009
Control[A]	6.85	6.62
Straw	6.88	6.59
Manure	6.84	6.70
Compost	6.86	6.75
LSD	n.s.	n.s.

[A] Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments.

The surface application of biochar appeared to significantly increase soil pH in both 2008 and 2009 (Table 4.10).

Table 4.10: Effect of surface application of amendments on soil pH.

	Soil pH	
	2008	2009
Control	6.82a[A]	6.52a
Biochar	6.92b	6.83b
Zeolite	6.84a	6.57a
B + Z	6.87ab	6.75b
LSD	0.044	0.084
p-value	p<0.001	p<0.001

[A] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.1.4 Soil exchangeable cations

The surface application of straw and manure gave a significant increase in exchangeable K after two years of application. The application of compost did not have any significant influence of the exchangeable cation levels in the plots (Table 4.11).

Table 4.11: The effect of surface applied organic amendments on soil cation levels.

	Calcium $cmol^+/kg$		Magnesium $cmol^+/kg$		Potassium $cmol^+/kg$		Sodium $cmol^+/kg$	
	2008	2009	2008	2009	2008	2009	2008	2009
Control[A]	39.7	35.6	8.7	7.2	3.8	3.15a[B]	1.7	1.24
Straw	40.6	35.7	8.9	7.4	3.9	3.75b	2.2	1.28
Manure	38.9	33.4	9.1	7.7	3.9	3.56b	1.6	1.03
LSD	n.s.	n.s.	n.s.	n.s.	n.s.	0.33	n.s.	n.s.
p-value						p=0.11		

[A] Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments. [B] Means followed by the same letter within columns are not significantly different at p≤0.05.

The surface application of biochar and half rates of biochar and zeolite together gave significant increases in exchangeable Ca in 2009. Biochar plots had significantly increased exchangeable K in both 2008 and 2009. By the end of the second year there was significantly less exchangeable Na in the biochar treated plots compared to the zeolite treated plots (Table 4.12).

Table 4.12: The effect of surface applied biochar and zeolite on soil cation levels.

	Calcium $cmol^+/kg$		Magnesium $cmol^+/kg$		Potassium $cmol^+/kg$		Sodium $cmol^+/kg$	
	2008	2009	2008	2009	2008	2009	2008	2009
Control[A]	40.0ab[B]	33.5a	8.9	7.4	3.8a	3.38a	1.8	1.19ab
Biochar	41.5a	37.3b	9.0	7.5	4.1b	3.64b	1.8	1.09a
Zeolite	38.8b	33.9a	8.8	7.4	3.6a	3.25b	1.9	1.29b
B &Z	39.51b	35.3b	8.8	7.3	3.8a	3.40a	1.8	1.22ab
LSD	1.62	1.05	n.s.	n.s.	0.28	0.13	n.s.	0.13
p-value	p=0.025	p<0.001.			p=0.031	p<0.001		p=0.033

[A] Control plots are the sub plots that do not have biochar or zeolite amendments but may have straw, manure or compost treatments

[B] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.1.5 Summary of effects of amendments on chemical properties

The surface application of biochar at a rate of 6 t/ha resulted in a significant 13% increase in total C after one year and one application and this had increased to 21% after two years and two applications. There were also increases in soil pH, exchangeable Ca and K (Table 4.13).

Surface applied manure applied at a rate of 10 t/ha resulted in a quick increase in available phosphorous and after two years there was a 140% increase in available phosphorous, 30% in total C, 18% increase in total N and 13% increase in exchangeable K.
The surface application of 10 t/ha of compost resulted in increases of 61% available phosphorous, 27% total C and 18% total N after two years and two applications.

The surface application of 10 t/ha of straw resulted in a 33% increase in total N and 25% increase in total C after two years and two applications.

The application of zeolite did not appear to benefit any particular soil chemical property compared to control plots.

Table 4.13: Percentage increase attributed to surface applied amendments above other treatment effects in field trial plots.

	TC		TN		P		pH		Ca		K	
	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
Straw		↑25		↑33								
Manure		↑30		↑18	↑49	↑140						↑13
Compost		↑27		↑18		↑61						
Biochar	↑13	↑21					↑1.5	↑5		↑11	↑8	↑8
Zeolite												
B & Z		↑8										

CVA results compared the result the treatments on the combination of chemical properties in which the 1st CV explained 88% of the variation for straw, manure and compost treatments and the 93% of the variation for biochar and zeolite treatments (Table 4.14). The 1st CV clearly separated manure, compost and straw treatments from the control with manure having the largest separation from control treatment (Figure 4.7). The 2nd CV shows that biochar had a greater impact on the combination of chemical properties than did zeolite (Figure 4.7).

Table 4.14: Values of latent vectors resulting from a CVA on significant chemical parameters.

Variable	Organic amendments		Other amendments	
	1st Canonical variate	2nd Canonical variate	1st Canonical variate	2nd Canonical variate
Variation (%)	87.85	7.48	92.74	5.51
TC (%)	2.9	-1.6	-6.5	-3.0
TN (%)	-8.6	6.0	46.3	26.3
Available P	-0.1	0.0	0.0	-0.0
pH	-2.9	-0.9	-1.9	10.3
Exchangeable Ca	0.1	-0.1	-0.4	-0.6
Exchangeable K	1.4	4.4	-0.9	-0.2

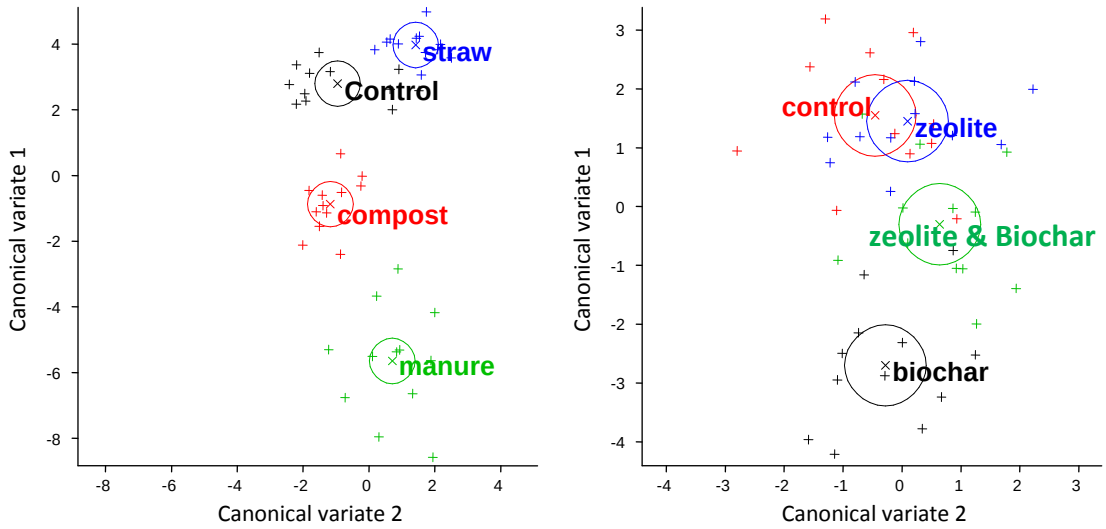


Figure 4.7: Plot of canonical variates (CV) generated by canonical analysis of soil chemical properties in Table 4.14 showing discrimination between a) organic amendments (straw, manure and compost) separated from control soils b) other amendments (biochar and zeolite and biochar and zeolite together with control. Circles surrounding treatments indicate 95% confidence region around the mean.

4.3.2 Changes in soil biological properties

4.3.2.1 Microbial biomass

The surface application of straw at 10 t/ha resulted in significantly higher microbial biomass than in control and manure plots in both 2008 and 2009 and than in compost plots in 2009 (Table 4.15). The surface application of manure at 10 t/ha after two years of application resulted in significantly higher microbial biomass than control plots.

Table 4.15: The effect of surface application of organic amendments on microbial biomass at wheat anthesis 2009.

Treatment	Microbial Biomass (mg Microbial C/100 g DM soil)	
`	2008	2009
Control[A]	36.9a[B]	33.1a
Straw	44.6b	52.6b
Manure	37.8a	42.2c
Compost	40.8ab	37.4ac
LSD	4.46	6.377
p-value	0.02	0.001

[A] Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments.

[B] Means followed by the same letter within columns are not significantly different at p≤0.05.

The surface application of either biochar or zeolite at 6t/ha after a two year period resulted in significantly less microbial biomass than that in control plots (Table 4.16).

Table 4.16: The effect of surface application of amendments on microbial biomass at wheat anthesis 2009.

	Microbial Biomass (mg Microbial C/100 g DM soil)	
	2008	2009
Control	39.1	46.08a
Biochar	40.6	40.39b
Zeolite	36.7	37.03b
B & Z	43.8	41.87ab
LSD	n.s.	4.607
p-value		0.004

[A] Control plots are the sub plots that do not have biochar or zeolite amendments but may have straw, manure or compost treatments

[A] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.2.2 Microbial community structure in 2009

The surface application of straw at 10t/ha resulted in significant population increases of amoeba, flagellates, ciliates and nematodes (Table 4.17). The total bacterial and fungal biomass was not altered at the time of testing by the addition of organic amendments.

Table 4.17: The effect of surface application of organic amendments on the microbial community structure at wheat anthesis 2009.

	Total Bacterial Biomass (µg/g)[A]	Total Fungal Biomass (µg/g) [A]	Total Amoeba (no./g) [A]	Total Flagellates (no./g) [A]	Total Ciliates (no./g) [A]	Total nematodes (no./g)[B]
Control	4.086	1.862	5.08a [C]	4.22a	2.37a	8.52a
Straw	4.593	2.551	7.37d	7.91b	6.33b	9.66b
Manure	4.240	2.224	6.11c	4.97a	3.32a	8.10a
Compost	4.329	1.924	5.81b	4.78a	2.63a	8.25a
LSD	n.s.	n.s.	0.0523	1.329	2.345	0.691
p-value			p<0.001	0.002	0.02	0.005

[A] Data was transformed by lnx [B] Data was transformed by ln (1000x+1)

[C]Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments.

[D]Means followed by the same letter within columns are not significantly different at p≤0.05.

The surface application of biochar and zeolite did not significantly influence the microbial community structure as at wheat anthesis in 2009 (Table 4.18).

Table 4.18: The effect of surface application of amendments on the microbial community structure at wheat anthesis 2009.

	Total Bacteria l Biomass (µg/g) [A]	Total Fungal Biomass (µg/g) [A]	Total Amoeba (no./g) [A]	Total Flagellates (no./g) [A]	Total Ciliates (no./g) [A]	Total nematodes (no./g) [B]
Control[B]	4.288	2.103	6.11	5.58	4.12	1.887
Biochar	4.338	2.109	6.16	5.66	3.32	2.160
Zeolite	4.407	2.175	5.8	4.95	3.86	1.911
B&Z	4.217	2.173	6.29	5.69	3.35	1.829
LSD	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
p-value						

[A] Data was transformed by lnx [B] Data was transformed by ln (1000x+1). [B]Control plots are the sub plots that do not have biochar or zeolite amendments but may have straw, manure or compost treatments

The interaction between surface applications of straw and zeolite resulted in a significant increase in total bacterial biomass at wheat anthesis in 2009 (Table 4.19)

Table 4.19: The effect of the interaction between the surface applications of amendments on the microbial community at wheat anthesis 2009.

	Total Bacterial Biomass (µg/g) [A]	Total Fungal Biomass (µg/g) [A]	Total Amoeba (no./g) [A]	Total Flagellates (no./g) [A]	Total Ciliates (no./g) [A]	Total nematodes (no./g) [B]
Control	4.211a [C]	1.756	5.42	4.67	2.00	8.68
SB	4.719a	2.447	7.89	8.27	5.97	10.16
SZ	5.043b	2.641	6.90	7.01	6.35	9.94
SBZ	4.360a	2.489	7.66	8.57	6.05	8.78
Straw	4.251a	2.626	7.03	7.77	5.97	9.76
MB	4.135a	2.117	6.09	5.03	3.14	8.54
MZ	4.370a	2.486	5.78	4.89	2.97	7.20
MBZ	4.157a	2.225	6.08	5.02	3.18	8.49
Manure	4.300a	2.067	6.48	4.95	3.98	8.17
CB	4.415a	1.851	5.55	4.79	1.90	8.25
CZ	4.130a	1.945	5.42	4.22	3.17	8.59
CBZ	4.381a	1.938	6.71	5.19	1.91	8.16
Compost	4.389a	1.963	5.53	4.93	3.53	7.98
Biochar	4.084a	2.020	5.10	4.56	2.28	8.68
Zeolite	4.083a	1.630	5.10	3.68	2.96	8.31
B&Z	3.969a	2.041	4.72	3.97	2.25	8.71
LSD	0.6151	n.s.	n.s.	n.s	n.s.	n.s.
p-value	0.043					

[A] Data was transformed by lnx+1 [B] Data was transformed by ln (1000x+1)
[C] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.2.3 Nematodes

The surface application of straw for two years at a rate of 10t/ha resulted in a significant increase in the population of bacterial feeding nematodes but a decrease in plant associated nematodes. Despite the lack of any plant feeding nematodes being detected in straw amended plots the difference was not significant (Table 4.20). There was a significant increase in bacterial feeding *Caenorhabitis and Panagrolaimus* abundance with surface applied straw. *Caenorhabitis* was detected in 100% of plots that had surface applied straw but in 9.3% of the plots without straw mulch (Table 4.20).

The surface application of manure for two years at a rate of 10t/ha resulted in a significant decrease in fungal feeding and plant associated nematodes (Table 4.20). Despite there being a significant increase in bacterial feeding *Teratocephalus* abundance with surface applied manure there was no overall significant difference in bacterial feeding nematodes between manure amended and control plots. The fungal feeding *Aphelenchoides* and *Bitylenchus* abundance was significantly reduced with either surface application of straw or manure but only the surface application of manure significantly reduced *Filenchus* and *Lelenchus* abundance (Table 4.20). The surface application of compost (Table 4.20), biochar and/or zeolite amendments (Table 4.21)) did not significantly result in any changes in the population numbers of various feeding groups of nematodes.

Table 4.20: Mean nematode abundance

Nematode Genus	Cp	Control	Straw	Manure	Compost	LSD	p-value
Bacterivores*							
Achromadora sp.	3	2.82	1.14	1.55	0.81		
Acrobeles sp.	2	0.80	0.48	0.78	0.82		
Acrobeloides sp.	2	2.60	1.46	3.02	3.28		
Caenorhabitis sp.	1	0.40a [A]	8.43b	0.00a	0.99a	1.541	p<0.001
Cephalobus sp.	2	4.78	4.55	5.23	5.24		
Cervidellus sp.	2	0.44	0.00	0.00	1.00		
Chiloplacus (pointy)sp.	2	0.40	0.00	0.48	0.40		
Chiloplacus (stubby)sp.	2	0.00	0.00	0.00	0.79		
Eucephalobus sp.	2	0.44	0.86	0.00	1.09		
Geomonhystera sp.	1	0.00	0.00	0.52	0.00		
Heterocephalobus sp.	2	5.81	4.80	4.32	3.94		
Monhystera sp.	1	3.32	1.95	3.17	3.38		
Panagrolaimus sp.	1	0.83a	4.05b	2.26b	0.00a	1.757	0.006
Plectus (lt)sp.	2	2.43	6.18	4.56	4.45		
Plectus (st)sp.	2	5.5	3.32	5.87	5.10		
Prismatolaimus sp.	3	4.23	4.67	4.96	5.36		
Pristionchus	3	0.44	0.00	0.00	0.00		
Prodesmodora	3	0.00	0.00	0.43	0.00		
Rhabditis	3	1.35a	0.9a	4.09b	1.24a	1.476	0.006
Teratocephalus	1	1.62a	0.50a	3.96b	2.42a	2.216	0.042
Wilsonema	2	0.00	0.59	0.86	1.53		
Total Bacterivores		**7.59a**	**9.29b**	**7.71a**	**7.58a**	**0.726**	**0.003**
Fungivores							
Aphelenchoides sp.	2	4.58	6.99	3.01	4.43		
Aphelenchus sp.	2	5.49a	2.06b	2.75b	4.74a	2.353	0.034
Aprutides sp.	2	0.00	0.00	0.37	0.51		
Ditylenchus sp.	2	5.13	4.94	4.10	3.36		
Epidorylaimus sp.	4	0.00	0.00	0.43	0.00		
Total Fungivores		**6.86a**	**7.95a**	**5.30b**	**6.18ab**	**1.436**	**0.020**
Omnivores							
Eudorylaimus sp.	4	1.99	1.91	2.23	1.58		
Microdorylaimus sp.	4	0.40	1.64	0.20	0.34		
Prodorylaimus sp.	4	0.00	0.00	0.43	0.00		
Thonus sp.	4	0.00	0.55	0.00	0.00		
Total Omnivores		**2.39**	**3.60**	**2.71**	**2.39**	**n.s.**	
Plant Associated							
Tylenchus	2	0.45	0.00	0.00	0.00		
Bitylenchus sp.	3	6.63a	2.63b	2.76b	6.07a	2.781	0.022
Cephalenchus sp.	2	0.00	0.00	0.00	0.43		
Filenchus	2	4.68a	4.40a	2.41b	3.74a	1.375	0.026
Lelenchus	2	1.34a	0.98a	0.00b	0.33ab	0.913	0.04
Total Plant Associated		**7.03a**	**6.31a**	**3.71b**	**6.29a**	**1.983**	**0.026**
Predators							
Clarkus	4	1.90	3.52	1.60	0.44		
Mylonchulus	4	0.40	0.99	1.87	0.73		
Total Predators		**1.96**	**4.51**	**2.86**	**1.16**	**n.s.**	
Plant Feeders							
Pratylenchus	3	4.06	0.00	1.21	2.81	n.s.	

*Feeding group as defined by (Yeates, Bongers *et al.* 1993); [A] Data was transformed (ln1000+1)

[C] Means followed by the same letter within rows are not significantly different at p≤0.05.

Table 4.21: The effect of surface application of amendments on the population of nematodes.

	Bacterivores (no./g) [A]	Fungivores (no./g)	Omnivores (no./g)	Predator Nematodes (no./g)	Plant associated (no./g)	Plant feeders (no./g)
Control[B]	8.00	6.45	2.73	1.76	5.47	1.35
Biochar	8.37	6.89	3.25	3.16	6.70	2.02
Zeolite	7.85	6.21	3.17	3.14	5.6	1.73
B&Z	7.95	6.75	1.19	2.44	5.57	2.98
LSD	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
p-value						

[A] Data was transformed (ln1000+1). [B] Control plots are the sub plots that do not have biochar or zeolite amendments but may have straw, manure or compost treatments

Surface application of straw and manure resulted in a significant rise in the proportion of bacterivores and decrease in the proportion of plant associated nematodes (Table 4.22)

Table 4.22: The effect of surface application of organic amendments on the proportion of nematode taxa as defined by Yeates *et.al*. (1993)

	Bacterivores	Fungivores	Omnivores	Predator Nematodes	Plant associated	Plant feeders
Control[A]	0.409a[B]	0.237	0.0135	0.016	0.250b	0.0752
Straw	0.694b	0.195	0.0197	0.022	0.068a	0.0000
Manure	0.703b	0.123	0.0227	0.075	0.062a	0.0140
Compost	0.537a	0.156	0.0155	0.006	0.255b	0.0308
LSD	0.1675	n.s.	n.s.	n.s.	0.1298	n.s.
p-value	0.014				0.015	

[A]Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments.
[B] Means followed by the same letter within columns are not significantly different at p≤0.05.

Surface applications of straw have resulted in a significant increase in the proportion of cp1 (coloniser) nematodes associated with a significant reduction in cp3 (persister) nematodes (Table 4.23).

Table 4.23: The effect of surface applied organic amendments on the proportion of coloniser and persister (cp) groups of nematodes.

	cp1	cp2	cp3	cp4	cp5
Straw	0.382b	0.501	0.074b	0.042	0
Manure	0.140a	0.546	0.214a	0.100	0
Compost	0.061a	0.565	0.352a	0.022	0
LSD	0.1275	n.s.	0.1385	n.s.	--
p-value	0.002		0.009		

[A]Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments. [B] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.2.4 Nematode ecological indices

The surface application of straw for two years resulted in a significant decrease in the maturity index (MI) and species richness index (SR) (Table 4.24).

Table 4.24: The effect of surface applied organic amendments on selected nematode community attributes.

	NCR	H' diversity	MI	λ	J_1	SR	No. Taxa
Control[A]	0.655	2.242	2.350a[B]	0.146	0.872	1.448a	13.25
Straw	0.778	1.927	1.776b	0.210	0.813	1.018b	10.67
Manure	0.863	2.208	2.273a	0.132	0.881	1.388a	12.33
Compost	0.770	2.261	2.334a	0.127	0.895	1.416a	12.67
LSD	n.s.	n.s.	0.3331	n.s.	n.s.	0.2857	n.s.
p-value			0.016			0.031	

[A]Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments [B] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.2.5 Microbial Activity

The surface application of straw resulted in significantly higher microbial respiration in 2008 (Table 4.25). There was no significant difference in q (CO_2) (respiration/microbial biomass) in either 2008 or 2009. In 2009 there were no significant differences of microbial respiration, activity of bacteria or fungi between treatments of surface applied organic amendments. (Table 4.25)

Table 4.25: The effect of surface applied organic amendments on microbial activity

	Microbial respiration (mg CO2)/hr/100g DM soil)		Metabolic quotient q(CO_2)		Active Bacteria	Active Fungi
	2008	2009	2008	2009	2009	2009
Control[A]	0.2392a[B]	0.1852	0.673	0.595	4.96	0.160
Straw	0.3607b	0.2751	0.869	0.539	7.01	0.726
Manure	0.2516a	0.2106	0.671	0.511	6.17	0.137
Compost	0.2628a	0.2011	0.649	0.561	5.46	0.525
LSD	0.06377	n.s.	n.s.	n.s.	n.s.	n.s.
p-value	0.012					

[A]Control treatment in this case are all major plots in split plot ANOVA that do not have straw, manure or compost but may have biochar or zeolite sub treatments. [B]Means followed by the same letter within columns are not significantly different at p≤0.05.

The surface application of biochar at 6t/ha over a two year period resulted in significantly higher microbial respiration and significantly higher q (CO_2) in 2009 (Table 4.26).

Table 4.26: The effect of surface applied organic amendments on microbial activity

	Microbial respiration (mg CO2/hr/100 g DM soil)		Metabolic quotient q(CO_2)		Active Bacteria	Active Fungi
	2008	2009	2008	2009	2009	2009
Control[A]	0.2785	0.2022a[B]	0.734	0.443a	5.92	0.624
Biochar	0.2950	0.2488b	0.734	0.656b	6.22	0.231
Zeolite	0.2657	0.1921a	0.638	0.532a	5.51	0.382
B & Z	0.2752	0.2290a	0.756	0.574a	5.94	0.624
LSD	n.s.	0.02741	n.s.	0.2123	n.s.	n.s.
p-value		0.001		0.005		

[A] Control plots are the sub plots that do not have biochar or zeolite amendments but may have straw, manure or compost treatments

[B] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.2.6 Summary of biological properties

CVA results comparing the combination of differences among treatments on significant soil biological properties indicated that there was 85% variation in the direction of the 1st CV for straw, manure and compost treatments and 55% variation for the biochar and zeolite treatments (Table 4.27). The combination of different proportions of biological properties clearly separated first straw and then manure amended soil from control soils as represented by the 1st and 2nd CV respectfully (Figure 4.8). The major impact for straw treatments appears to be the proportion of plant associated nematodes (- 3.67 in the 1st canonical variate) and second was the proportion of bacterivore nematodes (1.43 in the 1st canonical variate). For manure the major impact was the influence of proportion of bacterivore nematodes (-4.47 in the 2nd canonical variate) and second was the proportion of plant associated nematodes (2.24 in the 2nd canonical variate). The influence of compost was marginal on the biological properties of the soil and biochar and zeolite did not seem to have significant influences on the combined soil biological properties (Figure 4.8).

Table 4.27: Values of latent vectors resulting from a CVA on significant biological parameters.

Variable	Organic amendments		Other amendments	
	1st Canonical variate	2nd Canonical variate	1st Canonical variates	2nd Canonical variate
Variation (%)	84.81	12.7	54.68	39.24
Microbial Biomass	0.04	-0.04	-0.07	0.12
Amoeba	0.30	-0.18	-0.397	-0.26
Flagellate	0.55	0.24	-0.24	-0.21
Ciliates	0.20	0.17	0.754	0.16
Nematode	0.49	0.83	-0.44	-0.58
Proportion of Bacterivores	1.43	-4.47	0.564	-0.58
Proportion of Plant Associated nematodes	-3.68	2.24	2.35	1.23

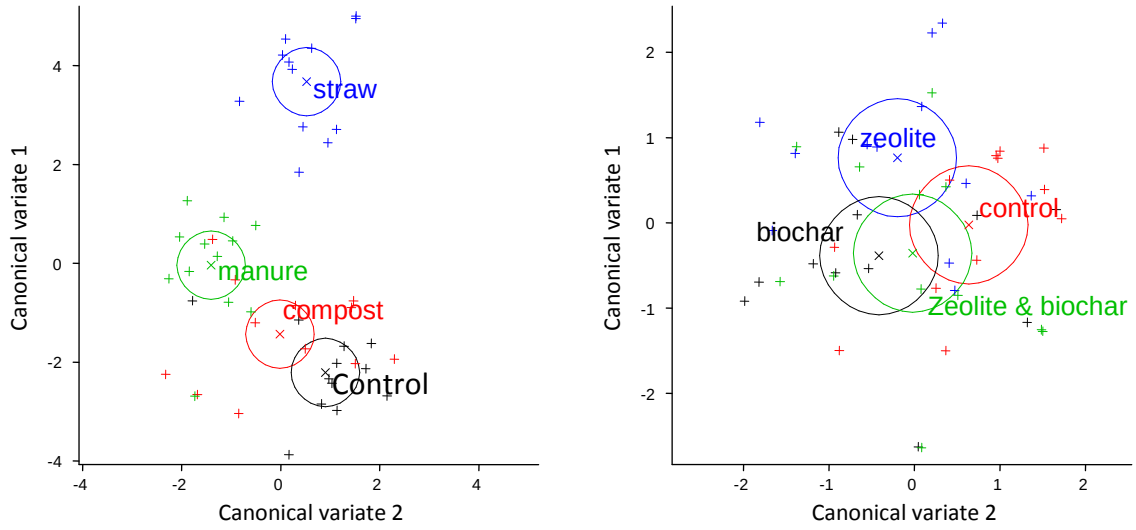


Figure 4.8: Plot of canonical variates (CV) generated by canonical analysis of soil biological properties in Table 4.27 showing discrimination between a) organic amendments (straw, manure and compost) b) other amendments (biochar and zeolite at 6t/ha and biochar and zeolite together at 3t/ha each) showing a 95% confidence region around the mean.

4.3.3 Changes in soil physical properties

4.3.3.1 Aggregate size distribution

The surface application of 10t/ha straw significantly increased the mean weight diameter (MWD) of soil particles in 2008 (Table 4.28).

Table 4.28: The effect of surface application of amendments on the MWD for dry sieved soils in 2008 in a) for organic amendments and b) biochar and zeolite amendments

a)

	MWD
Control	1.446a[A]
Straw	2.539b
Manure	1.618a
Compost	1.439a
LSD	0.6720
p-value	0.020

b)

	MWD
Control	1.591
Biochar	1.846
Zeolite	1.762
B&Z	1.844
	n.s.

[A] Means followed by the same letter within columns are not significantly different at p≤0.05.

4.3.3.2 Soil Moisture

The surface application of 10 t/ha straw significantly increased soil moisture during a fallow period in 2008 and during growth of wheat in 2009 (Table 4.29). The applications of other amendments did not significantly influence the moisture content of the soil in either year (Tables 4.29 and 4.30).

Table 4.29: The effect of surface application of organic amendments on soil moisture content.

	Moisture (%) Sept 2008	Moisture (%) October 2008	Moisture (%) October 2009
Control	23.05a[A]	28.14a	14.16a
Straw	29.78b	34.92b	15.59b
Manure	21.92a	28.49a	13.48a
Compost	23.59a	29.19a	13.76a
LSD	2.526	1.373	0.755
p-value	0.001	<0.001	0.001

[A] Means followed by the same letter within columns are not significantly different at p≤0.05.

Table 4.30: The effect of surface application of amendments on soil moisture content.

	Moisture (%) Sept 2008	Moisture (%) October 2008	Moisture (%) October 2009
Control	24.79	30.05	14.16
Biochar	25.34	30.36	14.22
Zeolite	24.63	30.28	13.97
B&Z	23.58	30.05	13.94
LSD	n.s.	n.s.	n.s.
p-value			

There is a significant positive correlation between the moisture content of the soil and abundances of various parts of the microbial population except for bacterial biomass (Table 4.31).

Table 4.31: The correlation between moisture and microbial abundances

	Soil moisture (%)
Total bacteria [A]	n.s.
Total fungi [A]	↑*
Amoeba [A]	↑***
Flagellates [A]	↑***
Ciliates [A]	↑**
Total nematodes [B]	↑**

[A] Abundances converted to ln(x) B Data transformed by ln (1000x+1)
*P<0.05, **P<0.01, ***P<0.001

4.3.4 Summary of changes to soil quality properties

CVA results comparing the effect of different treatments on the combination on the significant chemical, biological and physical soil properties examined in 2009 indicated that the 1st canonical variate explained 72% of the variation for straw, manure and compost treatments 85% of the variation for biochar and zeolite treatments (Table 4.32). This variation clearly separated manure and compost amended soil in one direction from control soil and straw in the opposite direction (Figure 4.8) when total N is the dominant factor involved (Table 4.32). Biochar amended soils were also clearly significantly separated from control soils with soils amended with half rates of biochar showing only half this separation (Figure 4.8). Zeolite amended soils were not clearly separated from control soils.

Table 4.32: Values of latent vectors resulting from a CVA on significant biological, chemical and physical parameters.

Variable	Organic amendments		Other amendments	
	1st Canonical variate	2nd Canonical variate	1st Canonical variate	2nd Canonical variate
Variation (%)	71.9	24.51	84.87	7.71
Microbial Biomass	-0.06	-0.07	0.03	0.10
Amoeba	-0.236	-0.17	0.08	0.29
Flagellate	0.29	-0.33	0.02	0.36
Ciliates	-0.15	-0.21	-0.03	-0.63
Nematode	-0.18	-0.09	0.17	0.09
Proportion of Bacterivores	-1.56	-3.35	-0.69	-0.91
Proportion of Plant Associated nematodes	-0.39	2.82	1.55	-2.08
Moisture	-0.44	-0.00	0.32	-0.68
Total carbon (%)	-0.83	4.74	-7.50	-0.48
Total nitrogen (%)	27.27	11.73	39.79	44.94
Available P	0.10	-0.03	0.02	-0.01
Exchangeable K	-3.22	-3.43	-1.47	-1.20
Exchangeable Ca	-0.12	0.09	-0.27	-0.03
Soil pH	2.96	-1.90	-3.28	0.45

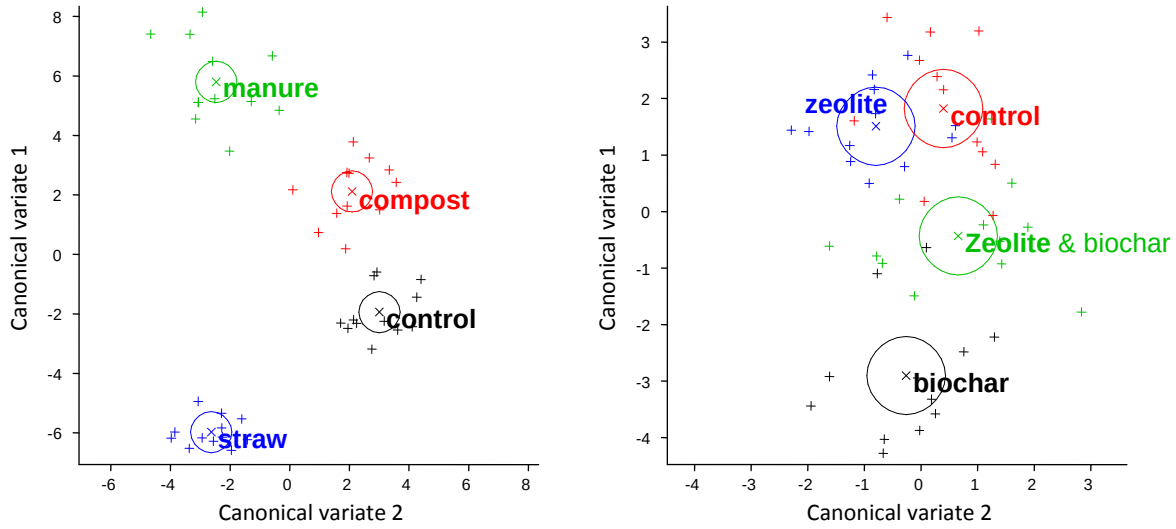


Figure 4.9: Plot of canonical variates (CV) generated by canonical analysis of soil biological, chemical and physical soil properties in Table 4.32 showing discrimination between a) organic amendments (straw, manure and compost) b) other amendments (biochar and zeolite at 6t/ha and biochar and zeolite together at 3t/ha each) showing a 95% confidence region around the mean.

4.3.5 Wheat yields

There was a wide range in wheat yields from 3.25 t/ha to close to 5 t/ha in individual plots in the field trial in 2009 (Figure 4.10). These yields were not significantly affected by surface

applications of amendments in either 2009 or 2010 (Tables 4.33 & 4.34). Wheat planted in 2009 was following a long winter and summer fallow period and wheat planted in 2010 was after a short summer fallow. Except for straw amended treatments the mean wheat yields were not reduced in the short fallow year compared to the previous long fallow crop (Table 4.33).

Table 4.33: The influence of organic amendments on grain yield (kg/ha).

	2009 Yield	WUE	2010 Yield	WUE	Average Yield
Control	4006	10.76	4182	9.62	4094
Straw	4343	11.66	4197	9.65	4269
Manure	4199	11.28	4413	10.15	4369
Compost	4303	11.56	4344	9.99	4324
LSD	n.s.	n.s.	n.s.	n.s.	n.s.
p-value					

Table 4.34: The influence of other amendments on grain yield (kg/ha).

	2009 Yield	WUE	2010 Yield	WUE	Average Yield
Control	4070	10.93	4372	10.06	4220
Biochar	4409	11.84	4220	9.71	4314
Zeolite	4265	11.45	4209	9.68	4237
B&Z	4107	11.03	4372	9.97	4220
LSD	n.s.	n.s.	n.s.	n.s.	n.s.
p-value					

A stepwise multiple regression analysis (McConway, Jones and Taylor 1999) of the combination of all the investigated soil properties on the effect of yield produced in 2009 resulted in the following fitted model with 34.6% of the variance accounted for:

Wheat yield (kg/ha) = -4.07 – 0.0665PF + 0.0706PA+0.578TB+0.832pH (equation 1)

Where: PF= ln (plant feeding nematodes); PA= ln (plant associated nematodes); TB= Total bacterial biomass; pH= soil pH.

The yield of the second crop of wheat sown after a previous wheat crop was significantly correlated to the previous crop yields (Figure 4.10). Variations around the line of best fit indicate that other factors are also involved but in general a yield of above approximately 4.3 t/ha seemed to have a negative influence on the following crop with up to 20% loss in yield for yields close to 5t/ha in the previous year.

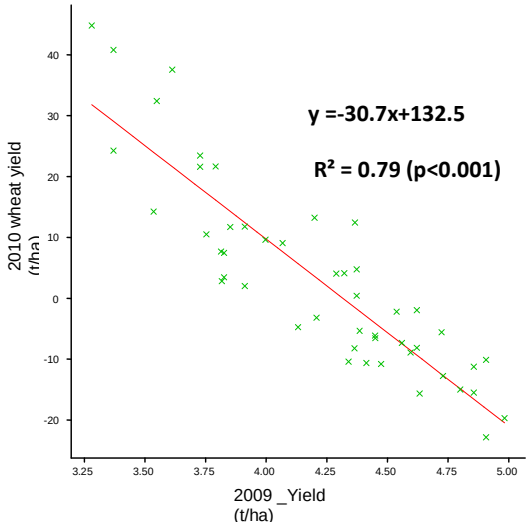


Figure 4.10: The correlation between the percentage differences in wheat yields with the yields of previous crop.

4.4 DISCUSSION

4.4.1 Effect on soil quality

4.4.1.1 Biological responses

The biological response to the surface application of amendments in this field trial was initially measured by the response of the microbial population in terms of SMB C. The intention in the fallow period of the field trial in 2008 was to observe any influences that amendments may have on the soil without the presences of living plants. During this time SMB C responded positively to the addition of straw applied on the surface at a rate of 10t/ha (Table 4.15). There are few studies that have measured the response by the soil microbes to the addition of organic amendments in no-till fallow situations. It is thought that fallow soil is low in easily available nutrients for the microbial community (van Bruggen *et al.* 2006) and that the addition of organic matter, especially if incorporated, will produce fluctuations in microbial populations in time-frames of days and weeks after incorporation (Zelenev *et al.* 2004). It is assumed that surface applied amendments result in a slower decomposition and ultimate release of nutrients from residue (Reeves, Mansoer and Wood

1996) which would be sustained over a longer period. Only the straw plots showed increased microbial biomass 6 months after surface applying the amendments. It is not known if the other amendments influenced microbial biomass at earlier times than the date tested. The application of straw also resulted in an increase in soil moisture (Table 4.29), presumably due to reduction of soil evaporation, so it is possible that this may have been a factor in promoting and prolonging the time-frame for microbial biomass increase. Associated with the 21% increase in microbial biomass in the surface soil under straw mulch the microbial activity increased by 51% during this fallow period. This is suggesting that this soil under no-till farming has the capacity to further increase its biological properties and that increased mulch or stubble cover could potentially overcome some of the negative influences on biological properties that may be caused by long fallows.

By 2009 during the growth of wheat and 9 months after amendments were applied for the second time, SMB C had responded positively to the addition of straw and manure with a 59% and 27 % increase respectively but negatively to either the addition of biochar or zeolite at a rate of 6t/ha (Table 4.15 and 4.16). SMB C was smaller but not significantly in plots amended with half rates of biochar and zeolite together. At the time of sampling the increase in SMB C appeared to be related to the increases in all taxonomic protozoan groups (ciliates, flagellates and amoebae) and total nematode abundances under straw mulch but only amoeba increased under manure applications (Table 4.17). There was a significant correlation between moisture and levels of protozoa and nematodes (Table 4.31) which were both significantly higher under straw mulch. The increased diversity of the protozoan community has been shown in other research to significantly raise the rate of wheat stubble decomposition compared to the presence of single species of flagellates alone (Gupta 1997). This rise in microbial biomass in straw amended soils was matched by a significant rise in the ratio of microbial biomass to total C in these soils. This indicates that per unit of C straw amended soil is supporting a larger microbial biomass population. The significant rise in soil moisture associated with the straw amendments may be helping to support this larger population and the risk without further inputs is that of soil C may deplete over time.

The total population of nematodes increased under straw mulch which appeared to be of the bacterial feeding type (Table 4.20). The proportion of bacterial feeding nematodes increased at the expense of plant associated nematodes. Nematodes are responsible for

nutrient release (Yeates and Pattison 2006) and in this trial it appears that in particular plant associated nematodes had a positive effect on yields in these soils when all factors were taken into account (equation 1). The proportional decrease of plant associated nematodes under straw mulch may have been a limiting factor on yields in this trial. The absence of plant feeding nematodes under straw mulch indicates that the associated yields were not limited by the presence of them.

The structural change in the nematode community is also associated with the increase in the proportion of nematode colonisers (cp1) at the expense of more persistent nematodes (cp3) in straw mulch plots (Table 4.23). Overall the straw plots seem to have reduced the maturity index (MI) and species richness (SR) nematode ecological indices (Table 4.24). While some genera of bacterial feeding nematodes such as *Caenorhabitis* and *Panagrolaimus* increased under straw mulch others such as *Rhabditis* decreased in abundance. A possible explanation could be that the surface application of straw produced a niche environment that enabled a small subset of the microbial community, which are normally quick to respond to ecological changes or disturbances due to their short life cycles, to increase their number and longevity. A change in the nematode community structure brought about by applying surface organic mulches is supported by the findings of other research where the population of bacterial-feeding nematodes were increased and root-knot nematodes were decreased when sun-hemp mulch crops were grown (Wang *et al.* 2008).

While it appears that straw amendments have influenced the microbial biomass and increased the proportion of bacterial feeding nematodes, the levels of total bacterial biomass despite being slightly higher did not significantly differ from control soils. A possible reason for this apparent contradiction is that bacterial feeding nematodes regulate the population levels of bacteria in the soil (Yeates 2003).

There was a slight but not significant increase in the level of soil fungal biomass in straw, manure and compost amended plots. The level of soil fungal biomass was seen to be decreasing in several no-till cropping soils of CW NSW and unlike soil C levels did not recover the longer the farmer practiced no-till (Chapter 3). Despite fungal biomass being significantly correlated to soil moisture ($R= 0.3292$; $p= 0.02$) the significant increase of

moisture under straw mulch did not result in significant increases in fungal biomass as it had with protozoan and nematode numbers. The cause may be due to overriding management activities that are depressing soil fungal levels even though tillage, which was identified as one such activity that depresses soil fungal biomass (Bailey *et al.* 2002; Tisdall 1991), is no longer practiced. One reason proposed may be the possibility of glyphosate having a fungicidal effect (Morjan, Pedigo and Lewis 2002). Glyphosate is frequently used in no-till agriculture which is known to inhibit protein synthesis via the shikimic acid pathway in fungi (Bentley 1990). The application to soil however at recommended rates has been shown to have only few and transient effects on soil fungi (Ratcliff, Busse and Shestak *et al.* 2006; Roslycky 1982). The change in substrates from complex lignin that favour soil fungi (Bittman *et al.* 2005) to more labile substrates may be a major factor in the reduction of fungal biomass in agricultural soils. Other factors may be the interactions of other parts of the microbial population or changes in soil properties. There is evidence that fungal feeding amoeba may decrease fungal hyphae lengths (Bonkowski 2003), reduce colonization of roots by ectomycorrhizal fungi (Chakraborty, Theodorou and Bowen 1985) and inoculum level and disease severity of pathogenic fungi (Chakraborty and Warcup 1984). Other researchers have linked variation in soil fungal biomass with variation in soil pH. There was no significant relationship in these soils between soil pH and fungal biomass but there was a significant ($p=0.039$) relationship between increasing fungal activity with decreasing soil pH ($R=0.2986$; $p=0.039$). Some research has indicated that soil fungal levels after initially responding to agricultural abandonment in a small way may take decades to fully recover from damaging agricultural practices (van der Wal *et al.* 2006).

In manure amended soils there was an increase in microbial biomass and this appears to be related to significant increases in the amoeba population. There was not the associated increase in soil moisture in the top 5 cm as there was in straw mulch amended soil so it might be assumed therefore that the amoeba although responding to increasing moisture levels were responding to other factors associated with manure. These results are similar to those found in a field trial in Sweden when amoeba responded to both manure and straw incorporation although they also found that flagellates responded to manure unlike in this trial (Schnurer, Clarholm and Rosswall 1985). While in this trial, the total population of nematodes in manure amended soils did not significantly differ from the control plots there

was a significant decrease in abundances of fungal feeding and plant associated nematodes balancing out the small and insignificant increases in bacterial feeding, predatory and omnivorous nematodes. As was the case with straw, the yields of wheat in the manure amended plots may have been limited by the decrease in plant associated nematodes. Individual genera of bacterial feeding nematodes that seem to positively respond to manure amendments are *Panagrolaimus, Rhabditis* and *Teratocephalus* (Table 4.17). These results contrast other studies that have shown positive effects of incorporated manure on both bacterivorous and fungivorous nematodes (Bittman *et al.* 2005) as well as omnivorous and predatory nematodes with reduction of plant parasitic nematodes (Nahar *et al.* 2006).

The application of compost did not appear to significantly influence microbial biomass or any specific microbial population except for a rise in amoeba numbers. This is despite the compost having similar properties to the manure amendment (Appendix 1). The biological components of the compost were rated good to excellent except for active fungal biomass and nematode population (Appendix 2). The high numbers of protozoa in the compost did not seem to influence the protozoan levels in the soil after the compost was surface applied. Similarly not all the genera of nematodes present in the compost were detected in the soil samples at the time of sampling. This is in contrast to other research that has demonstrated that microbial communities do positively respond to compost amendments (Nahar *et al.* 2006; Perez-Piqueres *et al.* 2006). The influence may be short lived as other research has demonstrated that applying 3.2 Mg of dry matter ha^{-1} of turkey manure and 6.6 Mg of dry matter ha^{-1} turkey manure compost showed that after 3 months there was a general increase of cultivable bacteria but this increase was not evident from 6 months onwards (Calbrix *et al.* 2007).

Biochar amendments did not have a significant influence on SMB C in the first year but by the second it was significantly reduced. This seems to contradict the analysis of the microbial community where all, except the ciliate population was slightly larger but not significantly more than those in control soils. It has been reported biochar can enhance the growth of microorganisms (Hamer *et al.* 2004) by stimulating microbes because according to Ogawa (1994) of the biochar properties of alkalinity (although rather weak), porosity and the ability to hold water. Different types of biochar produced from different material or

made at different temperatures can have different effects on the microbial biomass in the soil (Chan *et al.* 2008).

The reduction in microbial biomass in zeolite amended soils seems to be an overall general decrease and no significant downward trends were identified in any particular sections of the microbial community (Table 4.18). The addition of zeolite in the presence of straw did however give a significant rise to bacterial populations. This unexpected result compares with research showing that applying zeolite, compost and $CaCO_3$ together can result in a significant increase in microbial biomass compared to those treatments applied singularly or in groups of two and that bacterium seems to be promoted by the positive charged ion sites on zeolite (Chander and Joergensen 2002).

4.4.1.2 Microbial activity

While there were significant changes in microbial biomass in some treatments of the field trial it is known that measurement of the size of the microbial biomass is not necessarily an indicator of the level of microbial activity (Nsabimana, Haynes and Wallis 2004). Straw mulch appears to have caused a significant rise in microbial biomass and respiration during the fallow period of 2008 but only microbial biomass during the growth of wheat in 2009 (Tables 4.25 and 4.26). The presence of wheat plants in 2009 adds another layer of complexity to the effect of surface applied amendments on microbial population levels. It has been reported that root exudates promote microbial activity (Oger *et al.* 2004) and this may override the influences of amendments. It is interesting to note though that the microbial activity was less in all treatments when there was actively growing wheat compared to that in fallow soils.

Despite the decrease in microbial biomass in biochar amended soils there was an increase in microbial activity during 2009. This link between biochar and microbial activity is supported by various research findings (Nishio 1996; Ogawa 1994; Pietikainen, Kikkila and Fritze 2000; Zakrisson, Nilsson *et al.* 1996) despite the C source in biochar being more recalcitrant than the C in straw and manure which supports microbial decomposition. While it is acknowledged that the reasons for enhancement of soil microbial activity by biochar needs further research (Sohi *et al.* 2009), it is thought that biochar attracts microbial growth not necessarily through the breakdown of C but through other mechanisms such as electrostatic

bondage and hydrophobic effects (Mills 2003) or by providing a habitat for fungal hyphae in micropores that is free from competition (Sato and Marumoto 2002). The influences of other qualities of biochar, like the weak alkalinity which was shown to slightly lower fungal activity may off-set the habitat advantage for soil fungi.

4.4.1.3 Chemical properties

It was shown that soil C levels have been negatively affected by cropping in CW NSW even though these levels appeared to increase with the length of time that no-till farming was practiced (Chapter 3). The soil C levels in the field trial were shown to be reduced by at least 38% compared to levels in the adjacent non-cropped soil. After two years and two applications of straw, manure (6.3% C) or compost (14.5% C Appendix 1), soil C rose at least 25% compared to control soils and in biochar amended soils it rose by 21% (Table 4.13). Organic amendments are decomposed by microbial processes in which some C is lost as CO_2 but some C is stored within microbial cells adding to the total C in the soil. Biochar amendments are thought to be more recalcitrant to microbial attack than most organic amendments so the C increase caused by biochar additions is thought to last longer in the soil than that resulting from other organic amendments. This makes biochar amendments more useful in terms of contributing to longer term C storage and mitigating increasing atmospheric CO_2 concentrations (Lehmann 2007; Schmidt and Noack 2000).

The amount of C stored in the soil is the result of a long-term balance between plant production, respiration and decomposition (Ball 2006) and qCO_2 is an indication of how efficient the soil system is in storing C over time (Wardle and Ghani 1995). It is considered that higher values of qCO_2 indicate that there is greater net loss of C from the soil over time. Apart for biochar qCO_2 was not significantly different between treatments indicating that these treatments had similar levels of efficiency of using soil C and similar levels of sustained biological function.

There were similar rises in total N percentages to those of total C percentages creating insignificant differences in the C: N ratios in straw, manure and compost amended soils. Zeolite amended soils had a lower but not significantly different C: N ratios while biochar amended soils had significantly less total nitrogen than control soils and a significantly higher C: N ratio. Overall there was a significant correlation ($R=0.304$; $p=0.035$) between total N and microbial biomass. Stepwise multiple regression of the correlation between

total N and components of the microbial community determined that 37% of the variance in total N was accounted for by the population of amoeba and total fungal biomass ($p<0.001$). Soils that have higher microbial biomass and/or microbial activity are expected to have increased mineralisation (Six *et al.* 2006). Estimation of the amount of the amount of N mineralised attributed to the grazing of nematodes on microbes range from 30% (Verhoef and Brussaard 1990) to 83% of N mineralised by bacteria feeding nematodes and protozoa (Hunt *et al.* 1987). To be of optimum use for wheat plant growth the timing of this mineralisation is important in relation to plant uptake as nitrates it can be quickly leached in high moisture conditions.

After one application of surface applied manure available P increased by 35.5 kg/ha and after two applications this was further increased by 91.6 Kg/ha compared to control soils. The addition of manure has been found in other research to increase soil P levels in Vertosol soils in the short term (Ghosh *et al.* 2008) and in the longer term (Blaise *et al.* 2006) as repeated applications can reduce P adsorption capacity (Motavalli and Miles 2002). Soil P availability was not correlated to microbial biomass so it may be assumed that in these soils microbial biomass production was not limited by soil P levels as it can be in some soils (Sagger *et al.* 2000).

Two applications of compost significantly increased soil available P levels by 30.8 Kg/ha. While this is a significant increase it is well below the increase that was contributed by the application of manure. The increase in availability of soil P in compost amended soils unlike that of manure may be due to humus content. Humus is thought to increase soil P solubility by reducing the immobilisation of P with the formation of phosphohumic complexes, humate ions replacing anion P and humus coating sesquioxides particles to form a protective cover (Giusquiani, Marucchuni and Businelli 1988).

One application of straw resulted in a small but insignificant decrease in available P and after two applications there was a small but insignificant increase in available P compared to control soils. It is possible that the increased microbial biomass during decomposition of the straw may have immobilised P in the presence of increased quality and concentration of soil C (Stewart and Tiessen 1987). Despite research that suggest additions of biochar to soils increases the availability of P (Lehmann and Rondon 2006) there were little differences in

available P in biochar amended soil in this trial. There was a small but insignificant decrease in P availability in zeolite amended soils. It is thought that zeolite (alumina silicate) adsorbs P making it less available in the short term (Sakadevan and Bavor 1998).

Biochar additions caused a small but significant rise in soil pH. The increase ranged from 0.05 to 0.1 pH unit for surface applications of 3t/ha and 6t/ha respectively of biochar in 2008. During 2009 the increase had risen to 0.23 to 0.31 pH unit. The small but significant ($p<0.001$) rise in pH in the biochar plots is consistent with other research that indicates that biochar can cause an increase of up to one pH unit (Lehmann and Rondon 2006). Straw amendments resulted in a small but insignificant decrease in soil pH levels.

The small but significant increase in exchangeable K content in the top 0-5 cm of soil after two surface applications of straw and manure might be attributed to K content of straw and manure. The increase in exchangeable K content due to manure additions is similar to the findings of Ghosh *et al*. (2008) who also observed that exchangeable K levels are influenced by both crop uptake and clay type and also increased by the addition of compost. The increase of both Ca and K in the biochar amended soils may be contributed to the increase CEC of biochar. It is thought that biochar can increase soil CEC especially in the presence of organic matter (Liang *et al.* 2006).

In this study there were no significant differences among different amendments with respect to exchangeable Mg, but the mean concentrations were lower in all treatments in the second year.

4.4.1.4 Physical and abiotic soil characteristics

The increase in moisture content under mulch layers of 35% in the fallow year of 2008 and 15% during the growth of wheat in 2009 in the top 5 cm of soil is consistent with other research findings (Adams 1966). In times of frequent rainfall, mulches have been found to reduce evaporation. Surface mulch can reduce evaporation by 34-50% (Sauer, Hatfield and Prueger 1996). The reduction in evaporation by surface mulch is thought to be due to reduction in soil temperature, impediment of vapour diffusion and reduction in wind speed gradient at the soil-atmosphere interface (Grebb 1966). During heavier rainfall, mulches have also been found to increase infiltration and reduce run-off but during light and infrequent rainfall events the mulch has little effect on soil moisture levels (Allison 1973).

The amount of extra moisture that could be attributed to by mulch would therefore be a factor of the frequency and amount of rain as well as the thickness, absorbency and moisture holding characteristics of the mulch. The end result in the fallow soil of interactions of straw mulch cover with increased moisture content that facilitated higher microbial biomass was increased aggregate size of soil particles at least 6 months after application. This increased aggregation of particles creates better soil structure and can further aid water infiltration. There are normally dry periods during September and October in the region around the field trial. This corresponds to the flowering period of wheat and therefore a time of high water use by wheat. The water use efficiency (WUE) of wheat in 2009 increased from 10.76 kg/ha/mm in control plots to 11.66 kg/ha/mm in the straw amended plots an increase of 8% which is less than the 15% increase in moisture content. There was minimal difference in WUE in 2010. The WUE for all treatments in both years are well below 20 kg/ha/mm which is often considered the benchmark in deciding if variables other than moisture are limiting yields (Angus and van Herwaarden 2000).

4.4.2 Effect on crop production

The surface applications of amendments in this no-till system field trial resulted in significant improvements in several soil properties but the increase in yields over the two years was not significant. Further there was no one soil health indicator that was significantly correlated with yield. This suggests one of two things. Either the soil health indicators that were improved by organic amendments such as total C and SMB C in particular are not important for the commercial production of dryland wheat on these soils in this particular environment or alternatively the lack of correlation of these properties to yield might indicate that these soil health indicators are not at a constraining or critical level as described by Gonzalez-Quinones *et al*. (2011). The application of straw, manure, compost and biochar appeared to have different physical, biological and chemical soil properties from control soils with straw having the greatest biological response and biochar the most chemical response but these improvements in soil health properties did not cause significant increases in wheat yields. This is in contrast to yield increases attributed to organic amendments in other research but it has been noted that the largest differences between treatments have occurred during the driest cropping cycles and when amendments were applied with mineral fertilizers (Steiner *et al.* 2007) and the greatest

response of biochar occurs on nutrient-deficient sandy soils (Lehmann and Rondon 2006). The soil type in this trial was a higher quality of self mulching Vertosol and it may have limited short term response to organic amendments additions (Ghosh, 2008).

The wide range in yields (1.5 t/ha) was not related to treatments and this could indicate that the yield limiting factors were different to those soil properties measured the top 0-5 cm of soil. Alternatively the complex nature of the reactions of soil to surface applied amendments could mean that there were inconsistent changes to soil properties or the changes caused by amendments produced both beneficial and detrimental effects on yields. The main properties across all treatments that had major influences on the final wheat yield, accounting for 38% of yield variation, were increasing plant associated nematodes, total bacterial biomass and soil pH but increasing population numbers of plant feeding nematodes had a negative influence (equation 1). The high correlation of the yield of wheat in 2010 with the yields achieved in 2009 indicates that the yields below 4.3 t/ha in this soil do not negatively influence the following crop. Yields above 4.3 t/ha seem to have an adverse influence on the following crop of the same type. The limiting factors may have been increased disease or reduced available nutrients and/or reduced moisture levels within the soil profile. More research is needed to test which agronomic practices such as crop rotation, fertilizer use and length of fallow may overcome these limitations.

As well as insignificant effect on yields by the application of surface amendments there were insignificant differences in grain quality as measured by grain protein percentages, screening percentages and test weight (data not showed).

4.5 CONCLUSION

Surface applied amendments had various influences on soil quality but had little influence over wheat yields at least in the short term. The main disadvantages identified in chapter 3 of annual cropping in CW NSW was reduced soil C and SMB C especially that of soil fungal biomass section. All the amendments in this trial except for zeolite and half rates of biochar increased total C.

Straw amended plots also showed higher total N, microbial responses, moisture and aggregate size but these increases did not result in consistent increases in yield possibly due to decreases in plant associated nematodes. The microorganisms present in the soil under

straw mulch might enhance mineralization of organic matter but they would need ongoing inputs to balance the loss of soil C as CO_2 through decomposition to avoid depletion of soil C over time. The main advantage of straw mulch was its ability to change niche conditions within the soil which favoured natural microbial populations. Stubble was retained on the soil surface in this study but it has been shown that these soils are capable of responding to further additional levels of mulch. This may be achieved by growing higher biomass cash or cover crops that are grown quickly and the residues retained to produce thick mulch. There is an extra cost of improving the biological component of soil through the addition of mulch which may not be off-set by either increased yield or grain quality, unless other yield limiting factors are addressed. The longer term benefits need to be investigated.

Unlike straw that provided niche conditions especially through the increase in soil moisture, the application of manure was shown to increase nutritional elements such as available P and exchangeable K as well as soil N and C. Manure applications increased amoeba numbers and reduced both fungal feeding and plant associated nematode numbers. As was the case of straw, the improvements in soil properties did not necessarily influence yields. The lack of response of yield despite increased nutrients due to manure applications possibly indicates that the Vertosol may have had sufficient nutrients of the type were added.

Biochar was a more effective amendment than zeolite in benefiting soil quality parameters. These included increasing soil C, microbial activity, soil pH and increasing exchangeable Ca and K levels of the soil but microbial biomass was decreased. Biochar like all amendments did not significantly increase yields but when added to compost, there was less variability in yields than with compost alone. Compost resulted in improvements in soil C, nitrogen, and available P as well as increasing amoeba numbers. Unlike manure and straw, compost is a source of humus and although compost had a source of microbes (Appendix 2) they did not necessarily contribute to increases in protozoan or nematode populations. *Butlerius sp* nematodes were identified to be present in the compost that was applied to the soil but they were not subsequently identified in the soil later in the season. Zeolite had the least effect on soil properties and like biochar the microbial biomass was reduced but when it was applied with straw there was an improvement in total bacterial biomass.

It has been shown that it is possible to improve biological, chemical and physical soil properties with the application of surface applied amendments on a no-till wheat crop in CW NSW. Straw in particular seems to showing potential but requires a rate trial which will be presented in chapter 5.

CHAPTER 5
POT EXPERIMENT TO DETERMINE STRAW MULCH RATE TO MAXIMISE SOIL MICROBIAL PROPERTIES.

5.1 INTRODUCTION

The addition of surface applied straw mulch was shown to increase SMB C in the field trial in spring during a long fallow, as well as during a wheat crop the following year in a no-till paddock near Coonamble, CW NSW (chapter 4). In chapter 3, the farm surveys of cropping effects on grassland soil in CW NSW suggested that SMB C and in particular the fungal biomass portion were likely to be reduced after cultivation. Although the results of the survey suggested that SMB C levels generally recovered with the length of no-till, the soil fungal biomass levels did not. One hypothesis for the variation in response could be due to different substrate levels resulting from different stubble loads that are left in the field on no-till farming paddocks. Fungal biomass may require different stubble loads than are currently available in CW NSW no-till paddocks.

While SMB C may only account for less than 5% of soil organic matter it is considered to be an important sustainability indicator as it is a labile source and sink for C, N, phosphorous and sulphur, an agent of nutrient transformation, pesticide degradation, disease protection and soil aggregation as well as important for soil formation (Dalal 1998). Many benefits of SMB C are linked to soil and crop health issues that are thought to promote higher production. While the results of Chapter 4 were inconclusive about the levels of SMB C required to positively influence wheat yields in the years that the trial was conducted, the environmental benefits of reduced nutrient, water and pesticide run-off in soils with higher levels of SMB C would be justification for farmers to aim to have a fully functioning microbial system in cropping soils. It may also be argued that SMB C's role in pesticide degradation is especially vital in no-till agriculture due to the heavy reliance on herbicides to control weeds especially during the fallow periods (Chapter 3). The risk of herbicide pollution is potential damage to both human and ecosystem health (Salmon-Monviola *et al.* 2010). An increased level of SMB C may help soils to continue the process of pesticide

degradation and help reduce environmental contamination from pesticides although mulch and pesticide interactions are little understood (Liwang and Selim 2005).

The field trial in Chapter 4 did not show significant increases in bacterial or fungal biomass levels when straw mulch was applied during wheat production. These parameters were not tested during the long fallow period and it is possible that the response would be different when plants are not actively growing in the soil. The field trial also only investigated the effect of adding 10 t/ha of straw mulch. Varying rates of straw may have different effects on SMB C so it is now important to quantify the amount of mulch needed to maximise SMB C effects and if varying rates of mulch have an influence on the structure of the microbial biomass in the absence of plants. This study is designed to negate seasonal variations and factors such as mechanical disturbance which has been shown to have more effect than organic amendments on microbial changes (Calbrix *et al.* 2007). It is acknowledged however that physical disturbance cannot be avoided when soil is transferred from ground to a pot but it was aimed to minimize the level of soil disturbance where possible. The objective of this study was to determine the optimum rate of surface barley straw which could improve certain soil microbial properties of a Vertosol in a no-till farming system when no plants are growing. These properties include the size, activity and structure of the soil microbial community.

5.2 MATERIALS AND METHODS

5.2.1 Experimental design

A study to determine the short term effect of the rate of straw mulch on SMB C, bacterial and fungal biomass was conducted over 2 months from June 29 to August 30 2009 in the glasshouse in the Department of Agronomy and Soil Science, UNE. The experiment was conducted in a controlled temperature environment where the temperature was maintained between 17˚C and 30˚C (Figure 5.1) to simulate a day and night summer range of temperatures.

The experiment consisted of 15 pots each with 1 kg of soil but with varying rates of straw mulch placed on the surface. There were 3 replications of 5 different treatment rates of barley straw corresponding to 0, 5, 10, 15 and 20 t/ha (dry weight). No plants were grown in the pots. The pots were laid out in a randomized design with 3 replications. Soil moisture

was maintained near field capacity by monitoring pot weights twice a week and then watered when necessary. The gravimetric soil water content for this particular soil was measured to be approximately 364g/1000g at Field Capacity. Thermometers were placed in each pot and soil temperatures were monitored at regular intervals at mid afternoon for 2 weeks or until the soil differences between pots were consistently less than 1 degree C (Table 5.1).

5.2.2 Materials

The soil used, a cracking clay soil classified as Vertosol (Isbell 1996), was collected from the 0-5 cm depth in a cropping paddock at "Magomadine". The soil was taken from an area near the field trial as described in Chapter 4 that was also conducted at "Magomadine". The soil pH ($CaCl_2$) was approximately 6.8 and total C was approximately 1%. Particle size distribution was 69 g/100 g clay (less than 2 µm), 10 g/100 g silt (2-20 µm) and 21 g/100 g sand (20 µm - 2 mm). The barley straw that was used in this experiment was sourced from Coonamble. The barley stubble was originally processed into small bales after grain was harvested from a high yielding barley crop near Coonamble in December 2008 and stored under-cover at "Magomadine". On 9 June 2009 both bale of straw and 20 kg of soil were transported to Armidale. The straw was stored under-cover and the soil was kept in a cool room until the experiment was commenced on 29 June 2009. The pots of straw and soil were incubated in a glasshouse for approximately 2 months. The incubation period was halted on 2 September 2009, when sub samples of soil were packaged and posted immediately to the Lismore Soil Food Web Institute (SFI) laboratory for bacterial and fungal biomass analysis and the remainder was air dried in the glasshouse to be analysed for SMB C and respiration using the Substrate-Induced Respiration (SIR) method at UNE.

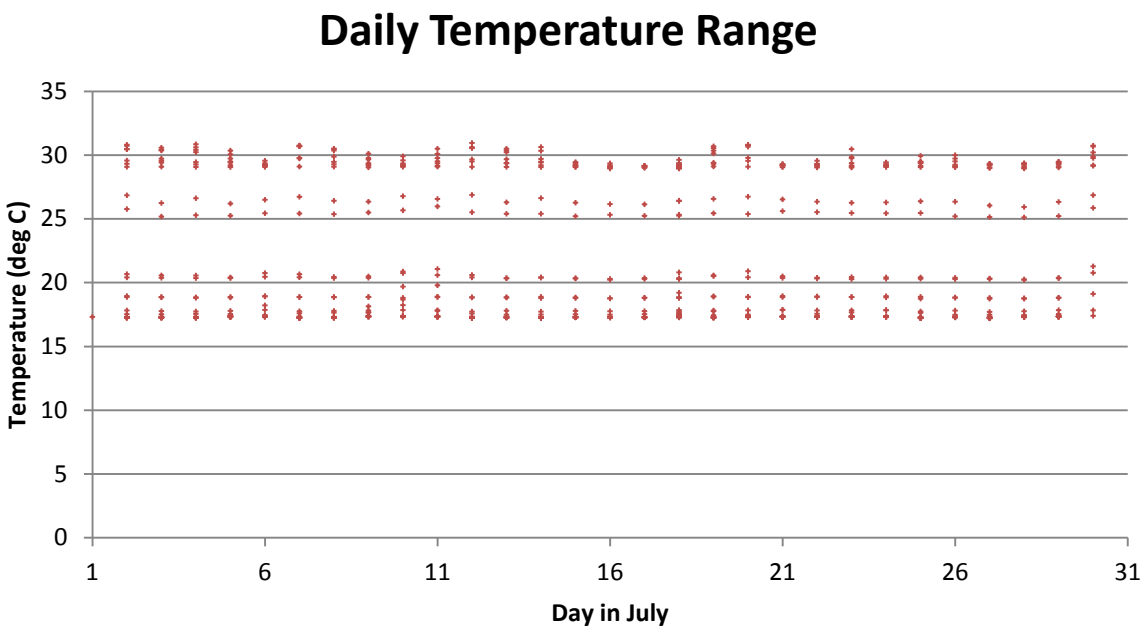


Figure 5.1: Daily temperature range in the glasshouse at UNE Armidale during July 2010.

5.2.3 Soil Analysis

Approximately 80 g of fresh soil samples were used to analyse the microbiological properties measured by SMB C and basal respiration using the method described in Chapter 3. Sub samples of the pot soil were to sent SFI laboratory for bacterial and fungal biomass and activity assessment as described in Chapter 3.

5.2.4 Statistical analysis

All data were subjected to analysis of variance. Residuals were examined for homogeneity and data were transformed where necessary to satisfy assumptions underlying the analysis of variance. Treatment means were separated using 5% LSD and those indicating significant differences were identified by different lower case letters. Statistical analyses were performed using Genstat statistical software.

5.3 RESULTS

5.3.1 Temperature

On the 1st day of incubation by mid afternoon there was a significant (P= 0.003) 4˚C difference between the control soil and soil that had the equivalent of 20 t/ha mulch applied on the surface to a depth of 1 cm (Table 5.1). During the following day this difference decreased and there were insignificant differences until measurement stopped being recorded on day 24. There was a similar pattern in temperatures differences between treatments at the 5 cm depth.

The soil was measured to be warmer at a depth of 1 cm by approximately 15 ˚C at the start of the experiment which narrowed to approximately 10 ˚C by the end of 24 days compared to the 5 cm depth.

Table 5.1: Effect of different rates of surface straw mulch on mean soil temperatures (˚C) at 1 and 5 cm depths. Date, time of recording, relative humidity and room temperature are included for each recording.

Date (2009)	30 Jun	1 Jul	3 Jul	6 Jul	7 Jul	8 Jul	9 Jul	10 Jul	13 Jul	14 Jul	15 Jul	16 Jul	17 Jul	20 Jul	21 Jul	22 Jul	23 Jul
Time (pm)			3.08	3.10	2.58	2.40	2.59	2.54	2.50	3.05	2.48	2.45	3.14	2.42	3.10	2.57	3.07
Relative Humidity (%)	24.1	20.2	19.4	21.1	26.9	26.9	27.1	48.8	24.3	20.9	19.9	24.8	24.2	14.2	27.3	30.5	19.1
Room Temp	30.7	29.4	29.5	29.2	29.3	29.3	29.3	29.0	29.1	29.2	29.0	29.2	30.6	29.8	29.3	30.2	30.4
Depth 1cm Treatment																	
control	29.0	29.0	29.7	29.7	27.3	28.3	28.3	29.0	28.3	28.7	28.7	29.7	30.3	30.7	30.3	30.0	30.0
5 t/ha	31.0	31.0	30.3	30.3	28.3	29.3	28.7	28.7	28.7	30.0	29.7	30.0	30.3	30.7	29.7	30.3	30.3
10 t/ha	32.3	31.5	30.3	30.7	28.3	29.3	29.0	29.0	29.0	30.0	29.3	30.0	31.0	31.0	29.7	30.0	30.7
15 t/ha	31.5	31.5	30.5	31.5	26.0	29.0	29.0	29.0	28.5	30.0	30.0	30.0	30.0	31.0	30.5	30.0	30.0
20 t/ha	33.0	31.7	30.0	30.3	28.7	29.3	29.0	29.3	29.7	29.0	30.0	30.0	30.0	30.7	29.7	30.0	30.0
Depth 5 cm Treatment																	
control	15.0	25.3	20.0	21.3	18.3	19.0	19.3	19.0	19.3	19.7	19.0	20.3	20.0	20.3	19.7	20.3	20.3
5 t/ha	16.7	26.7	20.0	21.0	18.7	18.7	19.3	19.3	19.3	19.7	19.3	19.7	19.7	20.0	19.3	19.7	19.7
10 t/ha	16.7	23.7	20.0	21.0	19.0	19.0	19.0	19.0	19.3	19.7	19.7	20.7	20.3	20.3	20.0	20.0	20.0
15 t/ha	16.3	25.7	18.7	21.7	17.7	18.0	19.0	19.3	19.0	19.3	18.7	20.0	20.0	20.0	19.3	19.7	19.3
20 t/ha	17.3	28.0	20.3	22.3	19.0	19.3	20.0	20.0	19.7	20.0	20.0	20.7	20.3	20.7	19.7	20.3	20.3

5.3.2 Soil microbial biomass carbon (SMB C)

Increasing rates of straw significantly increased SMB C to a maximum of 34.84 mg microbial C/100g DM soil, when the surface mulch rate was applied at a rate of at least 15 t/ha. This is approximately a 40% increase in SMB C over the control treatment (Table 5.2). The maximum level of bacterial biomass portion was measured to be 162.7 µg/g, which is approximately 171% increase over the control treatment. This occurred when at least the equivalent of 10 t/ha of straw mulch was on the surface (Table 5.2). The maximum level of fungal biomass was measured to be 64.8 µg/g, which is approximately 653% increase over the control treatment. This coincided with the equivalent of 15 t/ha of surface mulch (Table 5.2). There was no significant difference in levels of *Actinobacteria* biomass when straw was applied to the soil (Table 5.2). The ratio of total fungal biomass to total bacterial biomass (TF: TB) was significantly increased with at least 10t/ha of mulch and maximised with a rate of 15 t/ha (Table 5.2).

Table 5.2: Effect of the rate of barley straw mulch on biological soil properties compared to bare soil.

Rate of Straw (t/ha)	Microbial Biomass (mg Microbial C/100 g DM soil)	Total Bacterial Biomass(µg/g)	Total Fungal Biomass (µg/g)	Actinobacteria Biomass (µg/g)	TF:TB
0	20.9a	60.0a	8.6a	0.0	0.15a
5	22.7a	96.6a	15.7a	0.3	0.16a
10	25.7a	162.7b	35.8a	0.8	0.22b
15	34.9b	148.0b	64.8b	0.4	0.43c
20	33.3b	145.7b	51.4b	0.6	0.34b
LSD	6.1	50.03	28.87	n.s.	0.16

As the use of these biological measurements are relatively new in Australian scientific research following are results obtained by other Australian studies (Table 5.3) for comparison analysis. These indicate that an estimation of the interquartile range of SMB C in Australian cropping soils at a depth to five cm is 33 to 60 (mg Microbial C/100 g DM soil) but reduces to 19 to 55 (mg Microbial C/100 g DM soil) to a depth of 10 cm. SMB C measurements vary according to management of stubble, depth of sampling, season, land use and possibly soil type (Table 5.3).

Table 5.3: Estimations of microbial biomass (mg microbial C/100 g DM soil) in different Australian situations

Location/land use	Sampling Depth	Time of year	Number of Tests	Mean	Lower quartile	Upper quartile	Reference
Australian estimate [A]			175				
Cropping soils	0-5 cm				33 [A]	60	(Gonzalez-Quinones *et al.* 2011)
	0-10 cm				19	53	
Merredin WA [A]							(Hoyle and Murphy 2006)
Stubble burnt	0-5 cm	Autumn		~21			
Stubble retained	0-5 cm	Autumn		~30			
Stubble burnt	0-5 cm	Spring		~61			
Stubble retained	0-5 cm	Spring		~80			
Liverpool range NSW [B]	0-10 cm	Winter					
Cropping Vertosol		(control)	8	~20			(Nkem, Lobry de Bruyn *et al.* 2002)
Cropping Vertosol		(zero till)	8	~18			
Reference soil				~100			
Narrabri NSW [B]	0-10 cm	Spring	4	~42			(Ghosh 2008)
CW NSW [B]	0-5 cm	Autumn					Chapter 3 data
Cropping soil			20	39	30	46	
Grassland soil			10	86	49	100	
Coonamble district [B]	0-5 cm	Autumn					From data collected in Chapter 3
Cropping soil			12	40	33	45	
Grassland soil			6	101	60	134	
Field trial Site [B]	0-5 cm	Spring					From data collected in Chapter 4
Control		(long fallow)	12	36	32	39	
10 t/ha Surface mulch		(long fallow)	12	45	39	49	
Control soil		(wheat)	12	33	27	39	
10 t/ha Surface mulch		(wheat)	12	52	48	59	

[A] Various values from research data using different methodologies were adjusted by the authors to be equivalent to Fumigation Method (FE) to allow comparison between different methodologies. The values reported by the authors were then converted here to be equivalent to SIR estimates using the conversion ratio:

SIR-biomass C (mg/100g) = (FE biomass mg/kg C /0.75) /10 (Anderson and Joergensen 1997)

[B] Estimates of SMB C using the SIR method at University of New England

The mean and interquartile range for total bacterial biomass as measured by SFI varies in soils across locations, seasons and land use (Table 5.4). The lowest mean of 59 µg/g occurred in the control plots growing wheat in the field trial near Coonamble and the highest mean of 646 µg/g was in the grassland soil measured in six soils in the Coonamble district NSW (Table 5.4). Levels recommended by SFI range between 175 and 300 µg/g.

Table 5.4: Total bacterial biomass (µg/g) estimates drawn from unpublished data using the SFI lab

	Time of year	Number of tests	Mean	Lower quartile	Upper quartile	Reference
Central Qld	Autumn	30	157	60	256	(Stevens 2012)
Cropping soil 0-10 cm	Winter	15	446	266	618	
	Spring	30	550	349	710	
	Summer	5	420	319	510	
CW NSW	Autumn					(Chapter 3)
Cropping soil 0-5cm		46	465	316	615	
Grassland soil 0-5cm		23	513	380	626	
Coonamble	Autumn					(Chapter 3)
Cropping soil 0-5 cm		12	494	390	666	
Grassland soil 0-5 cm		6	646	510	732	
Field trial Site	Spring					(Chapter 4)
Wheat Crop	Control soil	12	59	51	67	
Wheat crop	10 t/ha mulch	12	115	64	145	
Recommended levels by SFI				175	300	

The mean soil fungal biomass levels for selected areas in eastern Australia as determined by SFI ranged from 7 to 119 (µg/g) with variations possibly due to depth of sample, season and land use (Table 5.5). The interquartile range of 29-87 (µg/g) for cropping soils in CW NSW is lower than 175-300 (µg/g) as recommended by that testing laboratory (Table 5.5).

Table 5.5: Estimates of total fungal biomass (µg/g) drawn from both published and unpublished data

	Time of year	**Number of tests**	**Mean**	**Lower quartile**	**Upper quartile**	**Reference**
Central Qld	Autumn (2007-2009)	30	32	11	53	(Stevens 2012)
Cropping soil 0-10 cm	Winter	15	19	8	24	
	Spring	30	13	7	16	
	Summer	5	36	23	56	
CW NSW	Autumn 2008; 2009					Chapter 3
Cropping soil 0-5cm		46	61	29	87	
Grassland soil 0-5cm		23	119	60	147	
Coonamble	Autumn 2008; 2009					Chapter 3
Cropping soil 0-5 cm		12	42	17	53	
Grassland soil 0-5 cm		6	89	53	118	
Field trial Site	Spring 2009					Chapter 4
Wheat Crop	Control soil	12	7	5	9	
Wheat crop	10 t/ha mulch	12	17	5	25	
Recommended levels by SFI				175	300	

5.3.3 Respiration and microbial activity

There was a significant 33% reduction in respiration with soil that had the equivalent of 10 t/ha of straw mulch on the surface compared to bare soil (Table 5.6). The SFI data however showed a significant increase in the activity of both the fungal and bacterial biomass, peaking with 15t/ha of straw mulch (Table 5.6). This increase in activity was an approximate increase of 365 % for bacterial biomass and 1029% for fungal biomass. The rate of straw did not significantly influence the ratio of active fungal to active bacterial biomass (AF: AB) (Table 5.6). At rates of 20 t/ha the activity of fungal biomass dropped to similar levels as the control. An examination of all data values confirms this decrease.

Table 5.6: Effect of the rate of barley straw mulch on soil microbial activity properties.

Rate of Straw (t/ha)	Respiration (mg CO2/hr/100 g DM soil)	Active Bacterial Biomass (µg/g)	Active Fungal Biomass (µg/g)	AF: AB
0	0.357a	6.92a	0.47a	0.06
5	0.368a	12.03a	0a	0.0
10	0.240b	25.23b	3.52b	0.13
15	0.386a	32.20c	5.31c	0.17
20	0.323a	23.57b	0.70a	0.03
LSD	0.08	5.5	1.5	n.s.

The mean for active bacterial biomass ranges from 5.0 to 39.0 (µg/g) in other soil analysis performed by SFI (Table 5.7). The interquartile range varies from 1.1 to 56.2 (µg/g) compared to the 1 to 5 (µg/g) range recommended by that laboratory.

Table 5.7: Active bacterial biomass (µg/g) measurements using SFI laboratory.

	Time of year	Number of tests	Mean	Lower Quartile	Upper	Reference
Central Qld						
Cropping soil	Autumn 2007-9	30	5.6	1.1	8.4	(Stevens 2012)
(0-10 cm)	Winter	15	6.1	1.6	91	
	Spring	30	4.8	1.8	6.0	
	Summer	5	4.0	2.8	5.4	
CW NSW	Autumn 2009					Chapter 3
(0-5 cm)						
Cropping soil		46	21.4	13.7	26.6	
Grassland soil		23	29.0	21.3	31.2	
Coonamble district	Autumn 2009					Chapter 3
(0-5 cm)						
Cropping soil		12	28.3	14.7	41.8	
Grassland soil		6	39.0	28.7	56.2	
Field trial Site	Spring 2009					Chapter 4
(0-5 cm)						
Control soil	Wheat crop	12	5.0	2.9	6.7	
10 t/ha Surface mulch	Wheat crop	12	7.0	2.5	9.3	
Recommended levels by SFI				1	5	

Table 5.8: Active fungal biomass (µg/g) measurements using SFI laboratory.

	Time of year	Number of tests	Mean	Lower quartile	Upper quartile	Reference
Central Qld						
Cropping soil	Autumn 2007-9	30	0.5	0	0.8	(Stevens 2012)
(0-10 cm)	Winter	15	0.5	0	0.8	
	Spring	30	0.4	0	0.3	
	Summer	5	0.3	0	0.6	
CW NSW (0-5cm)						Chapter 3
Cropping soil	Autumn 2009	46	3.2	0.5	3.5	
Grassland soil		23	6.3	2.4	6.5	
Coonamble district	Autumn 2009					Chapter 3
Cropping soil		12	2.2	1.9	3.2	
Grassland soil		6	7.9	1.1	7.5	
Field trial Site	Spring 2009					Chapter 4
Control soil	Wheat crop	12	0.2	0	0.2	
10 t/ha Surface mulch	Wheat crop	12	0.7	0.3	1.3	
Recommended levels by SFI				1	5	

5.3.4 Respiratory (metabolic) quotient (q CO_2).

At rates of straw above 5 t/ha there was a significant decrease in q (CO_2) (Figure 5.1).

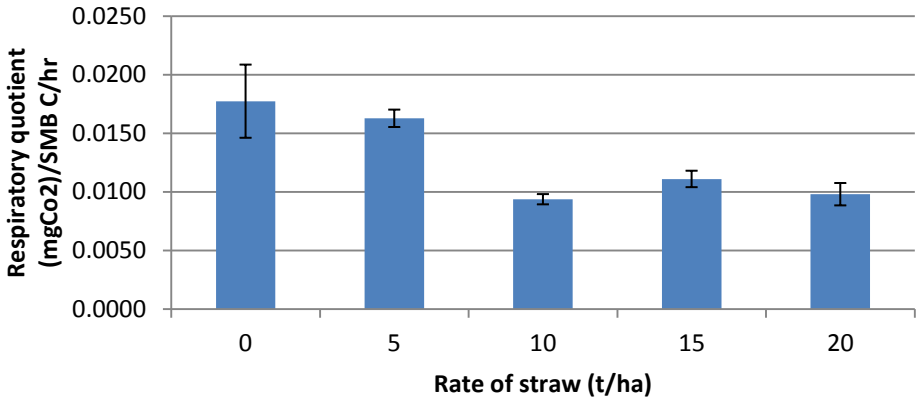


Figure 5.2: Effect of rate of straw on respiratory or metabolic quotient (qCO_2). Bars represent s.e. p= 0.014 LSD = 0.0057.

5.4 DISCUSSION

5.4.1 Soil temperature

The main determinants of microbiological biomass levels in soil are thought to be related to changes in temperature, moisture and organic substrates (Wardle 1992) as well as the soil characteristics such as texture (Dalal 1998). With this in mind this experiment was carried out with the same soil in controlled temperature and moisture conditions for all treatments except for varying level of surface organic substrates. During day 1 and 2 there were higher soil temperatures associated with increasing rates of straw at both 1 and 5 cm depths. On average there was a fairly strong correlation (R = 0.753; p = 0.002; accounting for 53% of the variance) between increasing rates and increasing soil temperatures resulting in a mean difference of 0.66˚C under 20 t/ha mulch compared to bare soil. While this is a small increase it is in contrast to other research that suggested that soil temperature is lower under mulch crops compared to unmulched crops (Alvarez *et al.* 1995; Bussiere and Cellier 1984; Lal 1974). It has been found that a 5 cm layer of mulch may reduce maximum surface temperatures by 8˚C and at a depth of 2.5 cm by 3˚C as soon as 4 days after mulch application (Bristow 1988). Decreases in soil temperature is thought to be largely attributed

to the effects of surface cover on energy transfer between the atmosphere and the soil surface (Grant, Izaurralde and Chanasyk 1995) resulting in less net radiation and evaporation from a mulch covered surface (Hares and Novak 1992).

The moisture content of soil also governs soil temperatures as water has a high specific heat and when combined with soil tends to moderate rapid changes in soil temperatures (Sylvia *et al.* 2005). Bristow (1988) found that there were no significant temperature differences between horizontal as well as vertical mulch compared with bare soils in wet conditions. As the pots in this experiment were maintained near field capacity this may explain the lack of soil temperature decrease as observed in field conditions with increasing levels of mulch.

Mulch also acts as an insulator reducing temperature extremes (Horton *et al.* 1996; Unger 1978) and this effect increases as residue mulch thickness increases (Unger 1978) so while soil under mulch may remain cool during the day the mulch can help to retain heat at night (MacDonald and Helgerson 1990). Soil temperatures can be increased by metabolic heat production through the rapid growth of bacteria which has been shown to increase in soil until bacterial substrate is used up at which point both bacterial population and metabolic heat production rate decline (Pamatmat and Findlay 1983).

The slight increase in soil temperature with increasing mulch layers in this study compared to decreasing soil temperatures in other research might be explained by maintaining moisture levels in all treatments near field capacity as well as the straw acting as an insulator storing heat, some of which may be originating from microbe metabolism.

5.4.2 Microbial biomass

In this study, varying rates of barley straw mulch had a significant influence on microbial biomass peaking at a 67% increase at a rate of approximately 15 t/ha (Table 5.2) on fine textured clay Vertosol. This is in contrast with other research that showed a much higher rate of 120 t/ha was needed to give 70% increase in microbial biomass when cotton gin trash was incorporated in Vertosol (Ghosh *et al.* 2011). The difference in rates required to significantly change the microbial biomass might be related to either the different mulch material used or the difference in surface and incorporated residues. Different mulch materials can result in differences in soil biological responses possibly due to different

chemical compositions especially N and lignin contents (Tian, Brussaard and Kang 1993). Other studies have shown that microbial biomass is increased with the different plant residues such as maize litter (Sharma, Rangger and Insam 1998) and triticale and winter pea (Schutter and Dick 2001) relative to non-amended soil.

Another possible reason for the differences in rates required to significantly change microbial biomass between those results found by Ghosh *et al*. (2011) might be due to the different mulch soil interactions caused by incorporation as opposed to leaving the mulch on the surface. It has been found that although cereal straw decomposes at a faster rate when incorporated with soil (Curtin*,* Francis and McCallum 2008) earlier research by McCalla (1958) found that there were higher microbial populations under residue mulch compared to incorporated residues. A pot trial study by Sharma, Rangger and Insam (1997) found that 1.5 cm under a 10 t/ha surface mulch had two to five times the value of microbial biomass, depending on soil type, compared to the corresponding bare control soil as well as soil that had the same rate of mulch incorporated into the soil. The incorporation of organic matter may change soil structure which can directly and indirectly influence microbial processes (Tejada *et al.* 2006). By contrast other research comparing effects of organic amendments and tillage has found that incorporation of organic amendments compared to surface application can enhance microbial properties but this occurs more so at a greater depth (Treonis *et al.* 2010).

5.4.3 Soil fungi

Cereal straw is a cellulose rich material (Harper and Lynch 1985) comprising about 40-45% cellulose and 35% hemicelluloses (Chang 1967) and is colonised by polymer degrading fungi when in contact with soil (Deacon 2006). Compared to soil bacteria the soil fungal hyphae allows more movement, colonization and degradation of surface litters (Holland and Coleman 1987). The soil fungi genera such as *Trichoderma*, *Aspergillus*, *Penicillium*, and *Fusarium* are important in the initial break down of cellulose (Sylvia *et al.* 2005). In this experiment an optimal rate of 15 t/ha of mulch created a 653 % increase in total fungal biomass production. Greenhouse studies by Doran (1980a) found that 14 t/ha of corn residue significantly increased soil fungal levels by up to approximately 3 times.

The microbial biomass appears to be more closely influenced by changes in fungal biomass which was also identified by Henriksen and Breland (1999) in a study investigating wheat straw decomposition combined in soil.

5.4.4 Soil bacteria

In this experiment an optimal rate of 10 t/ha of mulch created a 171% increase in bacterial biomass. The bacteria genera *Streptomyces* (Actinobacteria phylum), *Pseudomonas* (Proteobacteria phylum), and *Bacillus* (Firmicultes phylum) (Garrity, Bell and Lilburn 2004) are important in the initial break down of cellulose (Sylvia *et al.* 2005). One of the main phyla within bacteria, *Actinobacteria* (Boone *et al.* 2001) which is widely distributed in soil (Chun *et al.* 2000; Goodfellow and Williams 1983a) is important in decomposition and humus formation (Goodfellow and Williams 1983b; Lechevalier and Lechevalier 1967). In this study there was no detection of Actinobacteria biomass in control soil without mulch and although detected in most treatments with mulch the differences between mulch rates were insignificant. This is similar to results of other research (Treonis *et al.* 2010) in which organic amendments, either surface applied or incorporated, did not significantly change Actinobacteria levels in cropping soils. Other research has found that Actinobacteria are more likely to be found under surface mulch than in soils with incorporated mulch and were also more represented in residues left at the soil surface than in the soil itself. In this environment they can survive there possibly because of enhanced catabolic and/or survival strategies such as spore formation that allows survival in fluctuating moisture and temperature situations (Pascault *et al.* 2010). Research has found that Actinobacteria levels can be diminished in some herbicide treated soils (Barriuso *et al.* 2010).

The fungal to bacterial (TF: TB & AF: AB) ratios are used to determine the most active group of organisms that are degrading plant residues (Beare *et al.* 1990). In this experiment there was 199% increase in the ratio of total fungal to total bacterial ratio (TF: TB) at a mulch rate of 15 t/ha. In agricultural soils this ratio has been found to be lower than in more natural soils (chapter 4).

The decline in microbial biomass and in particular fungal biomass after 15 t/ha of mulch and bacterial biomass after 10 t/ha is applied might be explained by the limitations in nutrient

supply as it, along with moisture and temperature variations, affects the rate of decay of straw of surface residues (Deacon 2006). Nitrogen requirement for example has been shown to be twice that for bacteria compared to fungi (Sylvia *et al.* 2005).

5.4.5 Microbial activity

The reason for a one-off decline in substrate induced respiration with a mulch rate of 10t/ha is unclear. This was not reflected in either bacterial or fungal biomass activity as both increased with increasing rates of straw up to a mulch rate of 15 t/ha and declined with a rate of 20t/ha. Further research is needed to clarify the discrepancy between respiration and measurements of bacterial and fungal biomass activity.

The qCO_2 value decreased with mulch levels greater than 5t/ha. Lower qCO_2 values are thought to indicate a better utilisation of metabolic energy (Anderson and Domsch 1993) as less CO_2 is wasted from substrate utilisation which could lead to higher levels of soil organic matter accumulation (Wardle *et al.* 1999). A possible reason for higher metabolic quotients in low substrate situations, such as soils that are bare or with low levels of mulch, is the death of some microbes due to lack of available substrates with remaining ones using the contents of lysed cells for their own use (Dalal 1998). Higher qCO_2 levels are a possible indication of soils being under more stress or not recovering as well from disturbances (Wardle and Ghani 1995). Higher levels of qCO_2 in bare soil and soil with mulch levels of 5t/ha is therefore a possible indication that the microbial community is under more stress or has not recovered from disturbance as well as those soils with at least 10 t/ha of surface mulch.

5.4.6 Fungal decomposition of residues

Holland and Coleman (1987) summarised the advantages of a greater fungal decomposition compared to bacterial decomposition of residues. This includes a higher C assimilation efficiency by fungi compared to bacteria (Adu and Oades 1978) resulting in a higher proportion of fungal metabolised C being retained in biomass instead of being respired as CO_2. Fungal decomposition also results in less biomass turnover than bacteria as the more recalcitrant fungal cell walls decompose at a slower rate than bacterial cells (Kassim, Martin and Haider 1981). These experiments have shown that decreasing soil fungal biomass levels in CW NSW no-till soils may be overcome if there are higher residue levels left on the surface. To obtain 15 t/ha residues would require wheat yields of approximately 5.4 t/ha

and canola yields of 4.05 t/ha assuming average harvest indices (HI) of 3.6 and 0.27 respectively (Dunlop *et al.* 2008).

5.5 CONCLUSION

The application of differing rates of surface applied barley straw residues resulted in significantly different responses in microbial properties of a Vertosol. In order to maximise microbial and fungal biomass accumulation residue levels of approximately 15 t/ha (or wheat yields of 5.4 t/ha) would be required. These yields are higher than average yields in the Coonamble district but are achievable in higher rainfall areas of CW NSW. Lower yields of 3.6 t/ha of wheat or 10 t/ha of residue may result in maximum bacterial biomass accumulation.

These results indicate that under mild summer temperatures and when moisture is at field capacity these soils are prone to a higher qCO_2 than soils covered with mulch at more than 5 t/ha. Under these conditions it is feasible to assume bare moist soil or soil with minimum residue cover would accumulate less soil C than soils with higher residue cover. One possible way to lower the qCO_2 as well as regain some of the loss of soil fungal biomass, that appears to be lower in cropping soils of CW NSW, is to have the equivalent of 15 t/ha of residues. Stubble loads of this magnitude might be difficult to plant into depending on the type of seeding equipment used but knowledge that high surface residue loads are beneficial to soil microbiological properties may help farmers design systems that allow the maintenance of stubble and the ability to seed into it. It is important for farmers to make informed decisions about the feasibility of using straw which will be examined in chapter 6.

CHAPTER 6
STRAW USE FEASIBILITY ANALYSIS

6.1 INTRODUCTION

It was shown in the analysis of pot trials in Chapter 5 that 15 t/ha of straw mulch applied to the surface of cropping soil maximized SMB C and in particular the soil fungal biomass. It was also shown that 10t/ha maximised bacterial biomass. The soil was taken from a long-term no-till cropping paddock near Coonamble NSW and the pot trials were undertaken in response to the evidence presented in Chapter 4 that the application of surface applied organic amendments and surface mulch in particular (Table 6.1) can improve some ecological and soil health properties of this soil that may have suffered a decline from long-term cropping as other cropping soils in CW NSW have done as outlined in Chapter 3.

Despite the increases in the soil health properties during fallow and cropping periods in the field trial when straw mulch was applied, as indicated in Table 6.1, there was not an associated significant increase in wheat yield (Chapter 4). From this it might be argued that these particular soil health properties were not a yield limiting factor under the particular seasonal conditions during the time of the field trial. High residue cover may give environmental, rather than productivity or financial benefits, at least in the short term. While improving soil health properties are important from an ecological point of view and perhaps for the long term viability of cropping, these results indicate that yield responses from the addition of surface applied mulch cannot be guaranteed at least in the short term. If the cost of application is uneconomical it would limit the adoption of practices that are needed to increase residue levels which could maximise SMB C and in particular soil fungal biomass. It is therefore necessary to investigate the costs of surface application of mulch straw and other alternative methods which may also maximise residue cover. This would enable farmers to make informed decisions about the short term costs of improving soil health via increasing surface residues.

Table 6.1: Summary of significant effects of surface application of 10t/ha straw mulch on several soil parameters during a long fallow and a wheat crop on "Magomadine" Coonamble (Chapter 4).

	Fallow		Wheat production	
	Unit	Percentage	Unit	Percentage
Soil health properties	Increase	Increase	Increase	Increase
Moisture (%)	6.8	24%	1.4	10%
MWD aggregates	1.1	76%	n.a.	
Total nitrogen (%)	n.s	n.s.	0.03	33%
Total carbon (%)	n.s.	n.s.	0.3	25%
Potassium ($cmol^+/kg$)	n.s.	n.s.	0.6	19%
SMB C (mg Microbial C/100 g)[A]	7.7	21%	19.5	59%
Respiration (mg CO2)/hr/100g DM soil	0.1	51%	n.s.	n.s.
Total amoeba (no./g)	n.a.		2.3	45%
Total flagellates (no./g)	n.a.		3.7	87%
Total ciliates (no./g)	n.a.		4.0	167%
Total nematodes (no./g)	n.a.		1.1	13%
Bacterial feeding nematodes (no./g)	n.a.		0.3	70%
Plant associated nematodes (no./g)	n.a.		-0.2	-73%
Nematode Maturity Index	n.a.		-0.6	-24%
Nematode Species Richness	n.a.		-0.4	-30%

n.s. not significant n.a. data not available [A] The level of SMB C and soil fungal biomass maximized under straw mulch at a rate of 15t/ha in pot trials and bacterial biomass levels maximized under rates of 10t/ha. Both soil fungal and bacterial biomass were not tested during the fallow period (Chapter 5).

6.2 METHODOLOGY

The economic feasibility analysis of increasing soil residues involves an estimate of the costs of the purchasing, freighting and application of straw mulch and alternative methods which might also increase crop residues for wheat production on "Magomadine" Coonamble. This property is a commercial no-till farm in CW NSW. The costs used in this analysis are relevant to this particular farm. It is acknowledged that these costs may vary between farms in this region due to each farm's unique set of circumstances and distance from the source of straw mulch. This farm is typical however of the region where no-till agriculture is practiced. This involves controlling summer weeds through the application of herbicides, direct seeding into retained stubbles and controlling in-crop weeds through the use of selective herbicides and using GPS technology to control traffic movement in the cropping paddock (Chapter 3).

The first part of the analysis outlines the annual variable costs for the maintenance of the commercial crop that the field trial was conducted in during 2008, 2009 and 2010. These costs include the costs associated with maintaining a weed-free fallow, sowing wheat and weed control during crop growth as well as harvest costs. These costs are based on-farm prices and do not include freight costs.

The second part of the analysis examines an estimate of the amendment costs of buying, freighting and applying straw mulch that would be applicable for “Magomadine”. Different areas in CW NSW will have different freight costs depending on the distance the amendments need to be transported to the farm. The prices in this analysis, based on an approximation of current commercial prices was $100/t for baled straw with freight being approximately $3.50/km for hay sourced 90km away. The application of straw mulch is based on local contractor rates of using a chain spreader.

The third part of the analysis calculates the break-even economic crop yield in relation to varying rates of applying straw mulch and alternatives such as stubble mulching of a previous high biomass commercial crop or growing a cover crop for the purpose of producing high levels of biomass. The break-even yield is dependent on cash grain farm price obtained at “Magomadine”. The farm gate price for wheat has varied over the last 5 years between $112-$382/t, depending, not only on local seasonal events (such as weather damage at harvest and droughts), but also the international price of wheat which has widely fluctuated during this time. For the purposes of this exercise the average price of $200/t is used. The average paddock yields for wheat on “Magomadine” in the past five years have varied between 1 t/ha and 4.9 t/ha. As part of their risk management strategy, it is considered by the owners of this farm, that a break-even yield needs to be approximately 1 t/ha to avoid possible economic hardship in case of either low production or low commodity prices, or a combination of both. Break-even yield here refers to the yield that is required so that the total income is just equal to the total expenses on producing a crop at a given selling price (Kay, Edwards and Duffy 2004). The owners do their budgeting on a selling price of $150 /t.

The fourth part of the analysis examines the gross margin analysis of the field trial conducted on “Magomadine” (Chapter 4) for the control and straw mulch plots. The two gross margins refer to a wheat crop grown after a long and short fallow. The yields used in the gross margin analysis are the actual yields obtained in the field trial (Chapter 4). The range of on-farm wheat prices from $112/t to $382/t are used to examine the effect that commodity prices have on the break-even yields.

The last part of the analysis is an examination of the gross margin sensitivity for cover crop production as an alternative to applying straw mulch on cropping paddocks. The analysis involves examining long and short fallows as well as including opportunity costs of a previous commercial crop in the case of the long fallow.

6.3 RESULTS

Table 6.2 shows the actual total variable costs for each year of the field trial. The variable costs to produce the 2009 wheat crop were $250.47 which includes the 2008 long fallow costs of $74.70 combined with 2009 costs of $175.77. The variable costs for the 2010 crop were $184.43. The variation in costs associated with fallow herbicide depended on the number of times herbicides were applied as well as different types and rates of herbicides used.

Table 6.2: Calculations of variable costs for field trial paddock on "Magomadine" Coonamble for 2008, 2009 and 2010.

Operations	2008 Fallow ($/ha)	2009 Wheat ($/ha)	2010 Wheat ($/ha)
Fallow herbicide	39.70	35.14	13.78
Pre-sowing herbicide		14.18	11.70
Machinery	35.00	20.00	20.00
Sowing		29.50	29.50
Post sowing sprays		16.95	49.45
Harvest		60.00	60.00
Total variable costs ($/ha)	74.70	175.77	184.43

The summary of the economic analyses of applying surface mulch and the alternatives of stubble mulching high biomass crops or planting a cover crop in both a long and short fallow situation is presented in Table 6.3. The total cost to produce a wheat crop in a long fallow situation rose from $251/ha to $1594 /ha and $2265 /ha when straw mulch is applied at rates of 10 t/ha and 15 t/ha respectively which increased the break-even yield, for an on-farm grain price of $200/t, from 1.3 t/ha when no amendments were applied to 8.0 t/ha and 11.3 t/ha for a mulch rate of 10 t/ha and 15t/ha respectively. Similarly in a short fallow situation the break-even yields increase from 0.9t/ha when no amendment was applied to 7.6 t/ha and 11 t/ha for a mulch rate of 10 t/ha and 15 t/ha respectively. The cost of production, when previous high biomass stubble is mulched, is estimated to increase by $18

to $202.43 /ha having minimum effect on the break-even yields. The cost of production for cover crops are $309 /ha and $296 /ha for a long or short fallow respectively increasing the break-even yields by 0.2 t/ha to 0.6 t/ha respectively for an on-farm wheat price of $200/t.

The wheat gross margin analyses for the actual field trial on "Magomadine" after the long fallow demonstrated that the control plots that yielded 4 t/ha were profitable for a range of on-farm wheat prices from $112/t to $382/t (Table 6.4). The break-even price for the straw mulch plots was $370/t and $362/t for the long and short fallow crops respectively. During the short fallow the control plots and straw plots yielded the same but the high costs of the amendments meant that the break-even yield increased from $44/t in the control plots to $362 in the straw mulched plots.

Table 6.3: Economic analysis for applying mulch straw and alternatives for producing wheat.

Method	Rate t/ha	Variable cost $/ha	Amendment cost $/ha	Freight cost $/ha	Application cost $/ha	Amendment total cost $/ha	Total variable & amendment cost $/ha	Break even yield @ $200/t $/t
Long Fallow								
No amendment		251					251	1.3
Straw	10	251	1000	263	80	1343	1594	8.0
	15	251	1500	394	120	2014	2265	11.3
Stubble mulching	10	251			18 [A]	18	269	1.3
	15	251			20	20	271	1.4
Cover crop	10	304			5 [B]	5	309	1.5
	15	304			5	5	309	1.5
Short Fallow								
No amendment		184					184	0.9
Straw	10	184	1000	263	80	1343	1527	7.6
	15	184	1500	394	120	2014	2198	11.0
Stubble mulching	10	184			18 [A]	18	202	1.0
	15	184			20	20	204	1.0
Cover crop	10	291			5 [B]	5	296	1.5
	15	291			5	5	296	1.5

[A] Mulching costs of a previous high biomass commercial crop (e.g. sorghum)
[B] Costs associated with rolling down the cover crop in order to terminate it and to produce a mulch layer

Table 6.4: Gross margin analysis for wheat planted with and without 10 t/ha surface residues in a field trial on "Magomadine" Coonamble 2009.

		Yield (t/ha)	On farm wheat price: $112/t	$200/t	$382/t	Break-even Price $/t
After a long fallow:						
Control	Income	4.0[A]	448	800	1528	63
	Variable Costs		251	251	251	
	Gross Margin		197	549	1277	
	Break-even yield		2.2	1.3	0.7	
Straw	Income	4.3 [A]	482	860	1643	370
	Variable Costs		1594	1594	1594	
	Gross Margin		-1112	-734	49	
	Break even yield		14.2	8.0	4.2	
After a short fallow:						
Control	Income	4.2 [A]	470	840	1604	44
	Variable Costs		184	184	184	
	Gross Margin		286	656	1420	
	Break-even yield		1.6	0.9	0.5	
Straw	Income	4.2 [A]	470	840	1604	362
	Variable Costs		1527	1527	1527	
	Gross Margin		-1057	-687	77	
	Break even yield		13.6	7.6	4.0	

[A] Actual mean yield in field trials (Chapter 4). The higher yield in the short fallow trial is a direct consequence of higher rainfall that year compared to previous year (Chapter 4).

The gross margin sensitivity of cover crops used to replace the addition of straw mulch showed that for a low wheat price of $112 yields needed to be above 2.5t/ha for both a short fallow and long fallow cover crop to avoid economic loss (Table 6.5). If the opportunity costs of the commercial crop during the long fallow are taken into account then the break-even yields need to be above 4t/ha. For a wheat price of $200/t a short fallow cover crop needs to yield more than 1 t/ha, a long fallow cover crop more than 1.5 t/ha and 4t/ha if the opportunity costs are included. For prices of wheat at $382 both short and long fallow cover crops are profitable for yields more than 1t/ha but if opportunity costs are included then the break-even yield of a long fallow wheat crop is approximately 4t/ha.

Table 6.5: Gross margin sensitivity for wheat after growing cover crops to replace surface application of straw mulch.

	On farm price $/t:		
	112	200	382
	Short fallow cover crop		
Yield t/ha			
1.0	-179	-91	91
1.5	-123	9	282
2.0	-67	109	473
2.5	-11	209	664
3.0	45	309	855
3.5	101	409	1046
4.0	157	509	1237
4.5	213	609	1428
5.0	269	709	1619
	Long fallow cover crop		
1.0	-210	-122	60
1.5	-154	-22	251
2.0	-98	78	442
2.5	-42	178	633
3.0	14	278	824
3.5	70	378	1015
4.0	126	478	1206
4.5	182	578	1397
5.0	238	678	1588
Long fallow cover crop including opportunity costs of lost production			
1.0	-383	-629	-1137
1.5	-327	-529	-946
2.0	-271	-429	-755
2.5	-215	-329	-564
3.0	-159	-229	-373
3.5	-103	-129	-182
4.0	-47	-29	9
4.5	9	71	200
5.0	65	171	391

6.4 DISCUSSION

The break-even yields and gross margin analyses have shown that the application of straw mulch at levels required to significantly improve soil health properties on a cropping soil at "Magomadine" would most likely result in a financial loss unless the on-farm price of wheat is above $370/t combined with yields above 4t/ha. While these yields are achievable this

price of wheat has only been obtained on this farm once in the last 10 years. If on-farm straw waste is available then only the additional cost of spreading 15 t mulch ($120/ha) is applicable which reduces the break-even wheat yield down from 11.3 t/ha to 1.9 t/ha for long fallow wheat and from 11.0 t/ha to 1.5 t/ha for short fallow wheat for a wheat price of $200/t. This highlights that although the application of surface straw mulch may increase several soil health properties the cost of purchasing and freighting it is a considerable burden, which is unlikely to be recouped within one cropping cycle. This makes the growing of wheat after amended soil with 15 t/ha of mulch not only time consuming but uneconomical. Alternatively a higher yielding and/or a higher price alternative crop to wheat could be investigated or the use of on-farm waste straw of less economic value might be used to reduce financial risk.

The economic analysis shows that another cost effective method to build up higher level of residues is to utilise the biomass of the previous crops rather than to directly apply mulch. This might be achieved by stubble mulching the previous commercial crop (Christensen *et al.* 1994; Saffigna *et al.* 1989) or growing a cover crop with the specific purpose of creating surface residues (Hartwig and Ammon 2002b; Tonitto, David and Drinkwater 2005).

Improving the biomass of commercial crops might be achieved by genetic and agronomic means although recent advances in plant breeding have been to increase yield at the expense of lower plant biomass (Richards 1999). Agronomic means that can increase both yield and biomass include timeliness in control of weeds and diseases, improved nutrition and protection from frost, heat and water logging (Passioura 2006) while some of these may have an economic cost it is assumed here that timeliness of weed control and attention to detail are factors that do not have an economic cost but may increase biomass. There would be additional costs in improving nutrition or in using other methods to increase biomass which have not been identified here.

Cover cropping involves growing a high biomass crop which could be terminated by the use of herbicides or by rolling or crimping the leaves to produce thick mulch (Ashford and Reeves 2003). It is thought that by crimping and not breaking the stem (as in slashing) the plant does not regrow. The type of crop in this environment may need further investigation but a variety of plant types such as millet (Price and Castor 2007), sun hemp (Reeves,

Mansoer and Wood 1996), or rye and vetch (Sainju, Whitehead and Singh 2005) could be grown with the amount of biomass required to improve soil health properties as well as reducing the risk of disease that could build up from the same crop growing in its own stubble (Wang *et al.* 2008). As the plants are still anchored in the ground there is less risk of the residues blowing or washing away. The cost comparison of increasing surface residues by this approach is less than that of applying surface mulch (Table 6.2) and is a financially safer approach.

There are two possibilities of the timing of growing cover crops. The long fallow method involves planting the cover crop after the last commercial crop when there is sufficient moisture in the soil profile, then terminating it after the desired biomass is reached. The residues remain on the surface and planting of the following commercial crop occurs when the soil moisture levels are adequate. The length of this period is governed by the duration and frequency of rainfall events. This approach has the advantage that there would be sufficient surface residues in place to increase soil health properties but it would allow time for moisture to build up for the following wheat crop. The other method is to grow a quick cover crop between two annual crops (either two summer or two winter commercial crops). The risk using cover crops are possible yield reductions in times of limited rainfall (Warnes 1991). Research by Whish, Price and Castor (2009) into using cover crops in the northern grain zone of Australia showed that cover crops do not effect yields if they are terminated by December and time is given to replenish soil water by summer rainfall. They estimated that in the long term about 2% of years the rainfall may be insufficient to replenish soil water. There has been little research into what is required in CW NSW but it was shown by McNee *et al*. (2008) that while summer cover crops near Wellington CW NSW may reduce soil water compared to fallow soils their presence may help capture more water.

The economic analysis of using cover crops as a possible alternative to surface applied mulch demonstrated that it is a more cost effective method of establishing higher residue levels on annual cropping soils. The disadvantage is, if growing a cover crop replaces a commercial crop and if the associated opportunity costs are taken into account, wheat yields need to be 4.5 t/ha or higher to cover costs. If cover crops are grown without forgoing a commercial crop then wheat break-even yields could be reduced by as much as 25% and 50% to remain profitable for historic low and average priced wheat respectively. In

times of higher wheat prices this system remains profitable even if wheat yields as low as 1 t/ha are achieved by the following wheat crop.

The timing of the use of a cover crop may determine their profitability. With the use of long-range weather data and short term high biomass crops that may allow strategic planning and implication they may become profitable even with limited rainfall if they can be terminated early to allow soil moisture levels to fill again before wheat is planted. If there is no yield penalty in the following wheat crop after a short term cover crop then the gross margin analysis shows that this method is the most cost effective and profitable way to improve soil residue levels.

6.5 CONCLUSION

It has been shown that although surface applied straw mulch may increase certain soil health properties the purchase and freight costs can be quite inhibitory for their use in annual cropping systems. This cost may be reduced to just application costs if the farm had access to its own straw waste. The use of on farm straw waste on no-till farming paddocks could be a quite cost effective way to kick start biological improvement in cropping soils.

Alternatives to applying surface mulch such as stubble mulching and incorporation of the mulch was advocated as a system that could improve soil biological properties in the middle half of the last century (Mccalla 1958) it is not generally used in the no-till system in CW NSW, although one farmer in the soil surveys did occasionally use mechanical slashing (Chapter 3). Most of the farmers interviewed in the survey of practices in the CW NSW (Chapter 3) leave their stubble standing. The farmers often cited the risk of the mulched stubble washing or blowing away as deterrents for the widespread uptake.

The theoretical use of cover crops was investigated to determine economic viability. Cover cropping had been observed by some of the farmers surveyed to be extensively used in certain parts of North and South America to raise the residue levels of annual cropping soils. The economic analysis showed that if the cover crop resulted in the loss of production of one commercial crop then higher break-even yields of at least 4 t/ha are needed to be achieved to break-even. This is above the long term average of 3t/ha for this particular farm. If a long fallow is planned for other reasons such as a break for weed control to allow different herbicides to be used to avoid herbicide resistance then the opportunity costs of

the commercial crop need not be taken into account. The break-even yields are then reduced to 2.5t/ha or less if the price of wheat is above $112/t. The use of a long fallow cover crop in this case would be profitable and might allow an improvement in certain soil health properties during a time when they otherwise have been shown to decline (Bell *et al.* 2006).

A short-term cover crop may not replace a commercial crop but there may be a higher risk of lower yields with limited rainfall. Further research is needed to determine what circumstances are needed for yield increases in following crops, which types of crops benefit the most from cover cropping as well as to determine the number of years that the mulch lasts in the cropping system in this environment. These longer term factors would alter this economic analysis.

CHAPTER 7
GENERAL CONCLUSION

7.1 INTRODUCTION

There have been many reasons that no-till farming has been widely adopted throughout the world but there has been some research that the current practice, in certain regions of Australia, does not necessarily address the decline in soil C and SMB C that is often associated with annual cropping systems (Bell *et al.* 2006). The research in this Thesis aimed firstly to establish if there were any significant differences in relevant physical, chemical and biological soil properties between no-till cropped in both high and low productive areas with their corresponding non-cropped natural grassland reference soils in the CW NSW.

A survey of 40 annual cropping soils over two years demonstrated that total soil C and N, ammonia; Fe and Mn as well as microbial biomass, especially fungi biomass was significantly lower than the adjacent grassland reference soils (Chapter 3). There was an increase in the population of nematodes that feed on soil fungi in the cropping soils. There was a wide variation on individual farms in the response of soil C and microbial biomass to no-till farming but it was shown that generally the difference was smaller in soils that have been uncultivated for the longest time. On some farms no-till cropped soils had soil C levels higher than the corresponding uncultivated reference soils. Unlike soil C and microbial biomass, the fungal biomass proportion did not appear to respond as favourably to no-till farming. The apparent loss of soil fungal biomass may be one indicator of a possible future collapse in the no-till cropping system as currently practiced in CW NSW.

There was a wide variation of soil disturbance practices amongst the no-till farmers that were surveyed. While most no-till farmers used tyne no-till planters and avoided cultivation, there were a few that believed in a “strategic cultivation” that could be applied once over a period of many years without detrimental damage to the soil’s biological properties. The emphasis placed on crop residues also varied widely. Some of the surveyed farmers placed a lot of emphasis on improving the amount and total coverage of the soil, while a few saw residues as a problem at sowing and occasionally burnt their stubble to remove it from the system. The percentage of ground that was covered by crop residues

when the soils were surveyed varied from 8 to 100%. There was also variation in the frequency of cropping. While most soils were cropped annually, some were less frequently cropped and a small minority had two crops per year. Those farmers that cropped less than once a year typically had livestock in the system utilising the paddock when not cropped. They often saw that there was a trade-off of livestock controlling weeds and adding dung to the field with increased soil compaction. Most of the surveyed farmers that cropped annually kept the cropping and livestock operations apart in separate paddocks. While fertilizers were commonly used, about a quarter of the respondents had not applied fertilizer in the last five years. This wide variation of the no-till practice may be an underlying cause of the wide variation in soil C and SMB C levels measured in cropping soils. Further research is needed to ascertain "best practice" methods that influence these levels.

While there was a wide range of different practices of no-till, the most common ones that can broadly describe the surveyed CW NSW no-till soils, that they were managed to produce annual dry-land crops, were no cultivation of the soil, application of herbicides to control weed growth and seed planted into standing stubble with the use of tyne planters controlled by auto-steer technology which minimized the movement of machinery across the paddock. Livestock was also excluded from cropping paddocks.

In light of the apparent drop in soil C and SMC and in particular the soil fungal section, a field trial was conducted to ascertain if the addition of organic amendments applied on the surface of no-till soils might help to improve these parameters and wheat productivity. A farm in CW NSW was selected for a field trial to demonstrate if organic and other amendments can increase soil health, productivity and profitability of wheat in no-till farming systems. This farm was typical of farms using the above general practice of no-till farming techniques. These amendments included straw, compost, manure at a rate of 10 t/ha, biochar and zeolite at 6 t/ha and a combination of biochar and zeolite at 3t/ha. From results of this field trial, a series of pot trials were carried out to determine if varying rates of straw mulch had a corresponding effect on SMB C properties.

This current chapter highlights the major soil health findings in relation to each amendment, when soil samples were tested in spring, and outlines a number of future research directions.

7.2 ZEOLITE

The surface application of zeolite did not have any significant effect on soil health properties except for a 20% reduction in microbial biomass when 6 t/ha was surface applied. Zeolite did not appear to positively influence soil properties in these soils but further research in lower CEC soils may help to identify if the surface addition of zeolite can benefit crop yields through higher retention of nutrients. It is unclear why there was a reduction in microbial biomass and this may need to be investigated if zeolite is to be applied to soils. It is possible that if microbial biomass needs to be improved then the addition of zeolite may be counterproductive to that aim.

7.3 BIOCHAR

The surface application of 6 t/ha of biochar significantly increased total C by 21%, exchangeable Ca by 11% and K by 8%, soil pH by 5% as well as microbial respiration by 12% but microbial biomass was decreased by 23% (Chapter 4). Although there were no significant increases in wheat yields in this trial, yield responses to biochar may be more positive in soils with lower pH and lower exchangeable Ca and K levels than the levels that were in these soils. The combination of biochar and compost did not significantly increase yields (p=o.o6) although it did produce an overall 23% yield increase over the control. Additional trials using protocols that can reduce background variation and possibly adding more replications might help to understand the effect of adding both compost and biochar together on wheat crop yields.

The increase in total C was possibly due to the addition of inert and stable C in the biochar. The increase in microbial respiration coupled with a decrease in SMB C possibly indicates that more C is being respired than stored within the microbial biomass population. If this process continued it may be possible that more labile carbon may be lost to the system reducing soil C over time. This possibility as well as the possibility of different responses from different types of biochar, needs further research. As with zeolite, biochar additions may be counterproductive in increasing microbial biomass.

7.4 COMPOST

The addition of compost to these cropping soils, although not having a significant influence on selected soil health parameters during a long fallow, significantly increased Colwell P by 61%, total C by 27 %, and total N by 22% as well as amoebae populations by 14% during the wheat production year (Chapter 4). There was not a short term significant increase in wheat yields (Chapter 4).

7.5 MANURE

At $19/t cattle feedlot manure was the cheapest amendment purchased and freighted for use on the trial. The addition of surface applied manure to these cropping soils, during a long fallow, increased Colwell P by 36% and microbial biomass by 27 %. During wheat production manure significantly increased Colwell P by 140%, total C by 30%, total N by 22%, K by 13%, bacterial feeding nematodes by 72%, amoebae populations by 20% but decreased plant associated nematodes by 475%, (Chapter 4). Despite the increase in these properties there was not an associated significant increase in wheat yields in these soils (Chapter 4). Further research is needed to clarify why increasing P nutrition did not influence yields and whether there were other causes involved such as nutritional stratification or other constraints such as sub soil, soil water or nutritional restrictions.

7.6 STRAW MULCH

The application of straw mulch in the field experiment resulted in an overall higher number of improved soil health benefits compared to applications of manure, compost, biochar and zeolite. During the long fallow period the straw mulch plots showed an increase of 24% in soil moisture, 76% increase in mean weighted diameter of soil aggregates and 21% increase in SMB C (Chapter 4). During the wheat production period soil moisture was increased by 10%, total N by 33%, total C by 25%, K by 25%, SMB C by 59%, total amoebae population by 45%, total flagellate population by 87% and total nematode population by 13% with bacterial feeding nematodes increasing by 70% but plant associated nematodes decreasing by 73%. Other ecological changes in the nematode population were a reduction in nematode maturity index by 24% and nematode species richness by 30% (Chapter 4). These results suggest that mulch can correct microbial biomass decline during long fallow periods but plants may need to be included to address soil C decline. Further research would help

clarify this. The reduction in species richness and maturity index of nematode indicates structural change in the nematode community in response to mulch amendments. This may be a short term readjustment to changed environmental conditions caused by the mulch cover and more research is needed to understand if diversity will improve in the long term with constant mulch cover.

Despite the significant rise in microbial predators due to the addition of 10t/ha of mulch there was not a significant change in soil bacterial and fungal biomass in the field trials. It was shown in pot trials that these levels can be significantly changed by the rate of surface mulch (Chapter 5). It was shown by these pot trials that 10 t/ha of straw mulch can maximise bacterial biomass but 15 t/ha was needed to maximise both SMB C and fungal biomass (Chapter 5). It is unclear from this research what the cause of the lack of response of bacterial and fungal biomass to straw mulch application in the field trial compared to the increase found in the pot trials. Pots trials were conducted under field capacity conditions so it is possible it is a moisture related issue. It is also possible that bacterial biomass was at a maximum level in the field trial soil given the conditions at the time but fungal biomass levels may have been improved with 15 t/ha of straw mulch compared to 10 t/ha. Further research is needed to clarify this.

As with all the other amendments there was not an associated significant increase in wheat yields in two years of application of mulch at 10 t/ha (Chapter 4). While the increases in these soil parameters are important, in terms of soil health, their improvement via means of straw addition would not be profitable without an associated increase in yields. One way to reduce the costs would be to utilise on farm residues, or to either grow high biomass commercial or cover crops to produce more residues within the paddock (Chapter 6).

7.7 LIMITATIONS OF THIS RESEARCH

The main limitation of this research was the short term nature of the field trials and the limitation to a particular soil type within one area of CW NSW. The changes in cropping soil properties may occur over longer periods of time. It appears from the initial survey that no-till farming in CW NSW has the potential to increase soil C and microbial biomass the longer it is practiced. The variation between survey sites may be due to different practices within the no-till system and the results from the field trial and pot experiments suggest that the

level of surface residues left in the field after harvest are vital for sustaining favourable soil biological properties. A more detailed study to identify rates and diversity of surface crop residues to increase soil C and microbial biomass in the field would help to confirm this hypothesis.

The continuing decline in soil fungal biomass the longer no-till farming is practiced in CW NSW might be rectified by placing greater emphasis on increasing the levels of soil residues (Chapter 5). Pot trials were used to identify this but further field trials are needed to confirm fungal biomass response to levels of mulch, both with and without plants in the system. Another limit of this research was that only one mulch type was used. Additional research is also needed to examine the effects of the type and diversity of mulch has on varying soil biological properties as well as fungal biomass and what the limitations of different residues have on different crops in terms of possible disease risk.

The field trials failed to demonstrate, despite the increase in many soil health properties that organic amendments can significantly increase wheat yields. The wide variation in yields in each treatment was one limitation as the statistical analysis failed to highlight significant differences. The response of soil micro-organisms to organic amendments may vary across and down the soil profile due to the non-uniformity of soil niche conditions which may result in pockets of diverse microbe populations. For studies such as these it is possible that more replications are needed to differentiate treatment affects from background variation.

Another factor that influences yield response is the amount of rainfall. There was higher rainfall in 2010 and 2009 compared to 2011 on “Magomadine” (Chapter 4). The short term nature of the trial meant that both years that wheat was grown (2009 and 2010) in the field trial there were adequate rainfall events throughout the growing season for yields to be of a reasonable high level for this particular farm. During 2011, after the field trial was terminated, rainfall declined (Chapter 4) and anecdotal evidence in one particular paddock sown to wheat after a canola crop on “Magomadine” showed an increase in yields from 2.3 t/ha to 4.4 t/ha where high levels of straw mulch had accumulated compared to the rest of the paddock (Appendix 3). Field trials of longer duration might include lower rainfall years and more detailed research is needed to ascertain what conditions are needed for such

yield increases and if the yield increases are related solely to increased soil moisture or to increased soil biological properties as well. Comparing fumigated and non-fumigated mulch plots in varying moisture conditions may help in understanding this relationship.

This research was aimed at trying to identify what parts of the soil foodweb may be influenced by organic amendments and if they, in turn, can increase crop productivity. This approach had limitations in that it did not focus on microbial functions. Soil organisms are diverse and many different species may perform the same function. Future research may need to take this into account.

Finally the differences in soil parameters were only tested to a depth of 5 cm. This was done as most soil biological changes due to surface amendments would occur at this depth. The yield of crops while being influenced by the fertility of the topsoil is also driven by subsoil conditions. Future research may identify variability in subsoil conditions that may limit crop growth response to surface improvement in soil health properties.

7.7 FUTURE DIRECTIONS

Increasing soil biological health properties have been identified as being ecologically important (Chapter 2) and this research has shown that several of these properties can be increased by the application of surface applied amendments within the no-till farming system. Except for zeolite, the use of amendments has been shown to increase soil C levels and all except zeolite and biochar have been shown to increase SMB C. This research has shown that some organic amendments and in particular straw mulch can have not only a positive effect on SMB C but may also influence soil fungal biomass and microbial predator populations which are important for ecological sustainability. While an increase in predators is important for nutrient mineralization this research has not demonstrated a significant influence on crop yields at least in the short term. A model (Figure 7.1) which combines the data from both the field and pot trials might be used as a guide for future research. Items that have question marks indicate areas for in depth future study.

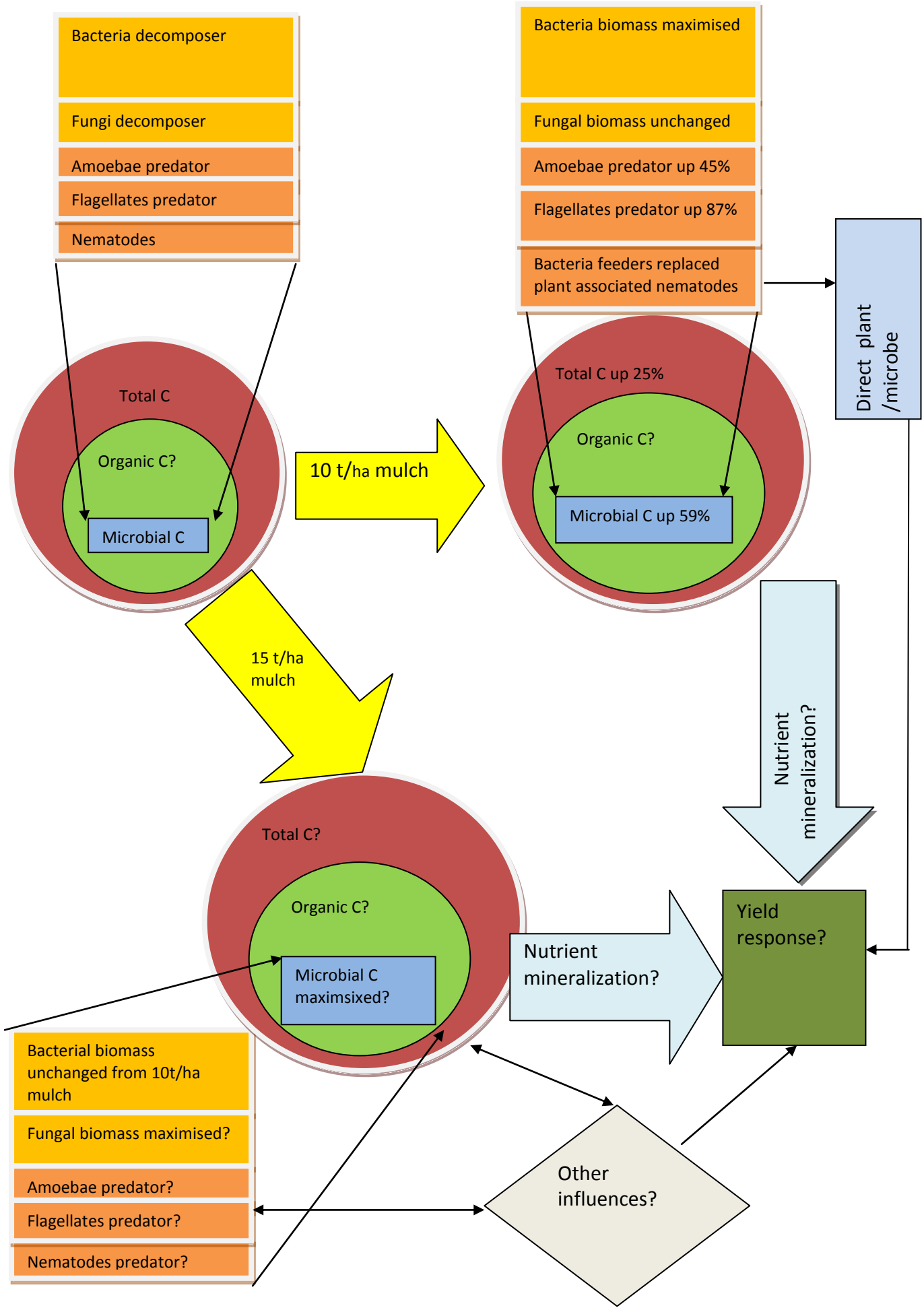


Figure 7.0.1: A possible model of the influence of organic amendments on crop yield

These areas may include an examination of the nutrient flow from the organic to the mineralized pool combined with the direct interactional effect that microbial changes such as nematode species change from plant associated nematodes to bacteria feeding nematodes has on plant growth.

Spatial differences in the physical, chemical and biological properties of soils may result in unpredictable results when organic amendments are applied to soil and when they are decomposed by living organisms. The amount of the SMB C is a result of an interaction of many influences some of which are outlined in Figure 7.1. Each of these six major influences has both positive and negative effects on the size of the SMB C as a whole as well as the size of the bacterial and fungal components. Soil characteristics include basic chemical and physical properties such as nutrient content and soil texture. Slight changes between these in each soil type may ultimately govern how the microbial biomass responds to the other layers. The soil environment includes the soil temperature, moisture and gases all of which can vary spatially across and down the soil profile as well as over time. The combination of the varying soil characteristics and soil environment create varying soil niches, some of which may be small in size that allow different microbial population to flourish and others to be dormant which may vary throughout the crop growing season. Microbial predation such as the levels of protozoa, nematodes and larger soil animals such as earthworms also has an influence on the level of microbial biomass. Their population size depends on the interaction from each of the other layers in Figure 7.1. The response of microbial biomass to these basic features of cropping soils is further influenced by human activity such as in plant selection, stubble management and use of agricultural inputs such as organic amendments, fertilizers and pesticides. It may be possible that the outcome of an application of organic amendment unlike the application of an inorganic fertilizer may be unpredictable due to small changes in these interacting factors. Statistical analysis of such a system may need to be similar to weather prediction and based on probabilities rather than

on predictable outcomes.

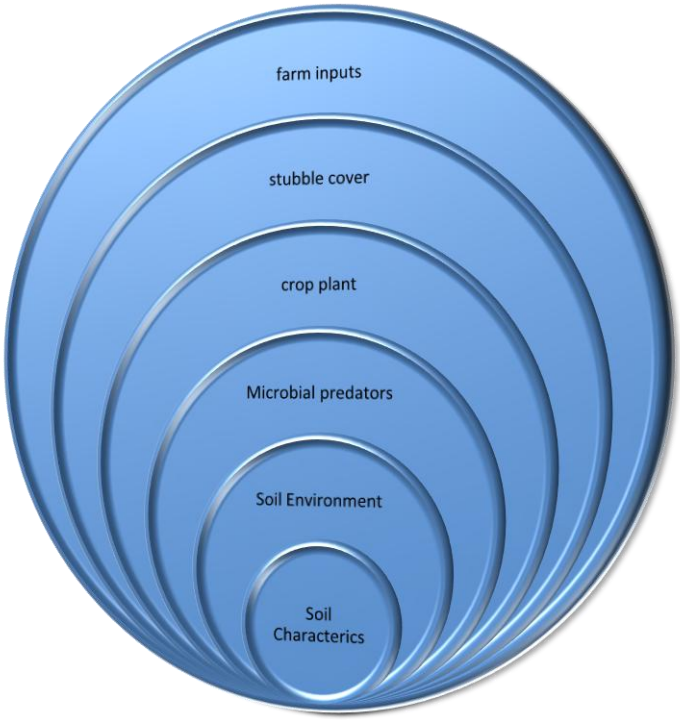


Figure 7.2: A venn diagram demonstrating the interconnecting factors that might influence the overall size and function of soil microbial biomass. Factors within each layer and different combinations of each of the layers can result in both positive and negative influences. It is possible that the response of the soil microbial biomass to application of an organic amendment (last layer) depends not only on the current state of each of the inner layers but also the unique combination of them. This might explain the unpredictability of response of organic amendments as opposed to inorganic fertilizer on soil function and yield.

This research has not clarified whether overall increases in SMB C or increases in only certain sections are beneficial for improved biological function of the soil or improved plant growth. In the soils of the field trial AM fungi were identified on wheat roots in only 9 of the 48 plots. This indicates that this soil was deficient in this area and that additions of amendments, at least in the short term, were not influential. While other research has identified these fungi to be of benefit to wheat production there have been studies that they can reduce yields in some crops if soil phosphorous levels are high (Pankhurst *et al.* 2003). Future research could be directed to clarify if this is also true for other functioning sections of the SMB C. A greater understanding of the relationship between soil microbes, their environment and substrate level as well as the level of predation and type of crop is needed in order to predict what effect these fungi and other sections of the SMB C have on crop production. The role of organic amendments may then become clearer.

It has been suggested that in soils of high natural fertility there is limited yield response to a change in SMB C (Bardgett and McAlister 1999). Further research on different soil types within CW NSW would help to identify which soils and conditions may assist crops respond to economically to the addition of organic amendments. The interaction between abiotic and biotic soil properties is complex and more research is needed before yield response can be guaranteed due to an application of a biological or organic amendment. The ability of the soil microbial population to recycle and mineralize plant available nutrients relies on a fully functional nutrient cycle. Breaks in that cycle can occur due to a decline of particular functioning groups of microbes (Albino and Andrade 2006). Further research is needed to determine if some aspects of no-till farming such as the high usage of certain herbicides, fungicides or insecticides may be having a negative impact on certain functioning groups. It is important that this knowledge would then become available to farmers so that they can make informed decisions on product selection.

Most modern wheat varieties have often been field tested with the use of artificial fertilizer and not necessarily organic amendments so it is possible there may be differences in plant/microbe interactions due to the use of different crop varieties. Further research would help to identify varieties of wheat and other grains that may respond to higher levels of microbial biomass and activity.

It has been found that annual cropping in CW NSW may have some negative ecological impacts such as reduced soil C, reduced microbial biomass and reduced fungal biomass which may or may not be affecting yields at this stage. Some of these can be addressed by avoiding cultivation over longer periods of time and by increasing the rate of surface residues. While long term no-till farming was observed to be addressing these issues and generally appears to be benefiting many soil properties it does not appear to be abating the decline of soil fungal biomass. A permanent decline in soil fungal biomass may result in a reduction in the fungal decomposition pathway of the soil food web as well as the predators that rely on it leading to reduced soil biodiversity. This decline might reduce future crop productivity by reduced nutrient recycling and mineralization and less water holding capacity of the soil.

Further research is needed to ascertain the reasons for the decline in soil fungal biomass. Soil fungi are an important part of a diverse and fully functioning soil microbial population. They are decomposers, especially of more “woody” material, recycle and redistribute nutrients, help fight some diseases, insect and nematode pests as well as being food for predators (Chapter 2). To reverse their downward decline, this research indicates that higher levels of residues may be needed than are currently being produced. While this research indicated that surface residues may need to be in the order of 15t/ha to significantly lift soil fungal biomass this needs to be clarified in the field. Further research on the most economical way of achieving this is also needed. Once the issue of fungal biomass decline is addressed then further research in the role of some organic amendments used as a fertilizer to replace the nutrients lost to the system by removal in grain may be beneficial. This approach may help no-till farming in CW NSW become less reliant on inorganic fertilizers at a time when the Australian economy is being encouraged to seek “low carbon” alternatives to help mitigate climate change.

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APPENDICES

Appendix 1: Summary of abbreviations, definitions and significance of soil biological terms

Abbreviation	Name	Units	Definition	Significance
TB	Total bacterial biomass	µg/g	Single cell micro organisms that at the time of testing are both dormant and metabolizing when viewed under the light microscope at 400X magnification.	The combination of diverse species have varying vital roles in plant decomposition, nutrient retention, disease suppression, micro aggregate formation, detoxification and nitrogen fixation.
AB	Active bacterial biomass	µg/g	Bacteria are stained to reveal those that are currently metabolizing.	The part of bacterial biomass that is working at the time of testing.
AB: TB	Ratio of Active bacterial biomass to total bacterial biomass		Obtained by calculation. Values range from 0 to 1. A value of 1 indicates all the bacterial biomass is currently active or metabolizing.	Gives a possible indication that the right food source (organic matter) is available, given a certain temperature and moisture conditions.
TF	Total fungal biomass	µg/g	Long threads of microscopic cells called 'hyphae' that are both dormant and metabolizing when viewed under the light microscope at 400 X magnifications.	Vital role in plant decomposition, nutrient retention, disease protection, macro aggregate formation for greater water absorption and retention.
AF	Active fungal biomass	µg/g	Hyphae are stained to reveal those that are currently metabolizing.	Indicates the part of total fungal biomass that is metabolizing at the time of testing
AF: TF	Ratio of Active fungal biomass to total fungal biomass		Obtained by calculation. Values range from 0 to 1. A value of 1 indicates all the fungal biomass is currently active or metabolizing.	Gives a possible indication that the right food source (organic matter) is available, given a certain temperature and moisture conditions.
TF: TB	Ratio of total fungal biomass to total bacterial biomass.		Obtained by calculation. Values close to 0 indicate bacterial dominance and above 1 fungal dominance.	Gives a possible indication of the potential of decomposition pathway being mainly fungal or bacterial dominant, given certain temperature and moisture conditions.
AF: AB	Ratio of the metabolizing fungal to bacterial biomass.		Obtained by calculation. Values close to 0 indicate bacterial dominance and above 1 fungal dominance.	Gives a possible indication of whether the current decomposition pathway is fungal or bacterial dominant
A	Amoeba	no./g	A type of predator protozoa feeding mainly on bacteria.	Gives an indication that nutrients, especially N are being released in plant available form.

Abbreviation	Name	Units	Definition	Significance
F	Flagellates		A type of predator protozoa feeding mainly on bacteria.	Gives an indication that nutrients, especially N is released in plant available form.
C	Ciliates		A type of predator protozoa feeding mainly on bacteria.	Gives an indication that nutrients, especially N is released in plant available form. Numbers greater than 100 per gram of soil can possibly indicate anaerobic / compacted condition
N	Nematodes		A predator that feeds on either bacteria, fungi, other nematodes or plants, numbers accessed by light microscope using 400 X magnification. diversity evenness	Gives an indication that nutrients, especially N is released in plant available form. They also consume disease causing organisms, and are themselves a food source for larger soil organisms. High numbers of root feeding nematodes can cause crop loss.
SR	Species richness		A nematode biodiversity index obtained by calculation using: $\mathbf{SR = (S - 1)/ \log_e N}$ where S is number of taxa identified and N the number of nematodes identified.	The higher the SR value, the more diverse and abundant a particular nematode species is.
H'	Shannon-Weiner diversity index		This is a diversity ratio obtained by calculation using: $\mathbf{H' = -\sum pi \log_e pi \ (i \text{ from } 1 \text{ to } S)}$ where p is the proportion of individuals in the *i*th taxon.	Higher values can indicate a more diverse nematode population, but as it may be dominated by abundant taxa or the overall number of taxa.
λ	Dominance index		A biodiversity index obtained by calculation using: $\mathbf{\lambda = \sum p_i^{\,2}}$ where p is the proportion of individuals in the *i*th taxon.	Lower values indicate a more diverse nematode population. Together with H' these indices can describe our diverse and stable the nematode population is.
NCR	Nematode channel ratio		NCR is a litter decomposition ratio ranging from 0 to 1, indicating the decomposition pathway is either bacterial (closer to 1) or fungal dominant (closer to 0).	Used together with TF: TB, NCR can help deduce if the decomposition pathway is diverse. Diversity allows for communities to quickly adjust to changes or stress.
J'	Evenness index		An index that reflects the degree of uniformity among a species' distribution. It is found by calculation using: $\mathbf{J = H'/ H'_{max} \text{ where } H'_{max} = \log_e S}$	

∑MI	Maturity index		An index that is found by calculation using: $\sum (cp_i \times i)$/ number of nematodes identified where i is the cp number from 1 to 5.	This is sometimes used as a gauge of the condition of the soil ecosystem.
cp	Colonizer (c) persister (p) number		This is a classification number which ranges from 1 to 5 with 1 being a colonizer, usually short lived to 5 persister and longer living nematode but takes time to build up population numbers.	The value can give an indication of the current ecological state of the soil environment. Low numbers could indicate recovery from stress or change and high numbers the community is stable without stress or change influences.

Source:
http://www.soilfoodweb.com.au/index.php?option=com_content&view=article&id=85&Itemid=117
Yeates and Bongers (1999)

Appendix 2: Analysis of compost and manure used on field trial plots at "Magomadine" Coonamble. Conducted by Southern Cross University, Lismore NSW.

	Nutrient	Units	Compost	Manure	Typical average Compost Nutrients
Total Nutrients (Acid Digest/Combustion)	Nitrogen (N)	%	1.66	0.97	2.0
	Phosphorus (P)	%	0.52	0.52	0.5
	Potassium	%	0.89	0.95	0.8
	Sulphur	%	0.2	0.23	<0.5
	Carbon	%	14.5	6.3	>30
Total Salts (Acid Digestion)	Calcium	%	1.95	1.3	3.0
	Magnesium	%	0.47	0.40	0.5
	Sodium	%	0.22	0.13	<0.2
Total Metals (Acid Digest)	Copper Cu	ppm	22	22	60
	Zinc	ppm	110	82	180
	Manganese	ppm	440	304	300
	Iron	ppm	17 532	19 847	12 000
	Boron	ppm	14	1.3	40
	Molybdenum	ppm	2.2	1.5	1.1
	Cobalt	ppm	4.2	5.0	11.2
	Silicon	ppm	1 899	1 327	1 200
	pH		7.4	6.9	
	Electrical Conductivity	dS/m	3.7	3.4	
	Moisture	%	37.2	32.8	
Other Total Metals (Acid Digest)	Aluminium	ppm	4 133	3 782	
	Selenium	ppm	0.41	0.42	
	Cadmium	ppm	0.12	0.03	
	Lead	ppm	10.00	3.92	
	Arsenic	ppm	1.2	1.37	
	Chromium	ppm	18	19	
	Nickel	ppm	8.8	8.6	

Acid Digestion: Sample digested with Aqua Regia acid for total nutrients/ salts and metals (NOT COMBUSTED PRIOR TO DIGESTION) Carbon/ Nitrogen/ Sulphur measured using a LECO CNS2000 Analyser.

Appendix 3: Biological analysis of compost for field trial on "Magomadine" Coonamble. Conducted by Soil Foodweb laboratory, Lismore NSW.

Organism	Unit	Level	Comment	Expected Range
Active Bacterial Biomass	µg/g	94.5	Excellent	15-25
Total Bacterial Biomass	µg/g	2336	Good	100-3000
Active Fungal Biomass	µg/g	7.13	Low	15-25
Total Fungal Biomass	µg/g	115	Good	100-300
Hyphal Diameter		2.5		
Protozoa:				
Flagellates	no./g	67 809	High	10 000
Amoebae	no./g	84 704	High	10 000
Ciliates	no./g	846	High	50-100
Total Nematodes (Butlerius genus Bacterial Feeder)	no./g	4.99	Low	20-30

Microbial measurements determined by direct microscopy were carried out on fresh, undried compost, and expressed on a per dry weight basis. Gravimetric dry weight of compost samples was determined.

Appendix 4: Effect of extra mulch on a no-till paddock during a dry year

a b

c d

Plate 1: Photos demonstrating the influence of high residues levels on plant emergence and final yields during a year of limited rainfall on "Magomadine" Coonamble 2011. a and b: wheat emerging through clumps of high residue. c: Ripening wheat crop where straw clumps had been present at sowing. This section averaged 4.4 t/ha when hand cuts were taken and grain released with a portable battery operated harvester. Adjacent area away from the mulch areas were measured to yield 2.3 t/ha d: Ripening wheat where there was limited residue cover. The paddock average for this wheat crop was 2t/ha.