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ALTERNATIVE PRACTICES FOR OPTIMISING SOIL QUALITY AND CROP PROTECTION FOR MACADAMIA ORCHARDS, LIMPOPO PROVINCE, SOUTH AFRICA

BY

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DECLARATION

I, Jacobus Nicolaas Steyn, hereby declare that this thesis for a Doctor of Philosophy in Ecology and Resource Management degree at the University of Venda, hereby submitted by me, has not previously been submitted for any degree at this or other university, and that it is my own work in design and execution and that all reference material contained therein has been duly acknowledged.

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ABSTRACT

The main aim of the research was to contribute means for converting conventional, high-input production systems to more sustainable ecological systems, thereby improving the sustainability of macadamia production and ultimately contributing to food security. This was achieved by a) investigating the potential use of cover crops and compost to enhance soil quality in macadamia orchards and b) investigating the potential use of use of cover crops and orchard heterogeneity to control stinkbug pests that target macadamia crops.

Field experiments were conducted in three phases: phase one tested the potential of six cover crops for crop protection (as trap crops) and simultaneously for soil restoration or fertility enhancement purposes in macadamia orchards. Phase two repeated the trials of phase one (both soil restoration and trap crops) but with modifications to both categories. Soil restoration treatments were conducted with trees which were growing in what appeared to be healthy soils, and then repeated with trees in the same orchard where the topsoil had been degraded (totally removed) by agricultural operations. The third phase repeated the trap crop trials only, but this time on three different study areas (all commercial farms) with the single cover crop which performed the best as a trap crop during phase two. Trials were modified from the first to the last phase to overcome practical implementation problems encountered along the way and to adapt to local conditions experienced in the commercial macadamia farming systems which served as research sites. Diversity of natural orchard vegetation was enhanced in phase three to improve conditions for natural predators as part of the trap crop treatments in the last phase and cover crops were finally first composted and then returned to the root zones of the macadamia trees as part of the soil quality enhancement treatments in the second phase.

The results from the trap crop trials shows a significant effect of trap crops combined with increased orchard diversity in reducing unsound kernel percentages caused by stinkbug pests and demonstrate that trap crops combined with an increase in orchard diversity could be utilized in macadamia orchards as a more sustainable alternative to inorganic pesticides against the stinkbug complex.

The most notable changes in the soil that took place with soil quality enhancement treatments were the significant increases in soil phosphorous content and pH which resulted not in an improvement in soil quality in terms of these two indicators but revealed an important issue about the use of compost containing animal manure originating from dairies or feedlots. In summary however, it was clear that although not all the soil quality indicators that were employed to assess changes in the soil with compost treatments improved significantly, a holistic consideration of all indicators portrays an overall improvement which was particularly significant in the degraded soil plots where the topsoil had been removed by prior agricultural activities.

Key words: Cover crops, trap crops, ecological sustainability, soil quality, crop protection, habitat heterogeneity, compost and macadamia.

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TABLE OF CONTENTS Page

CHAPTER ONE: INTRODUCTION

1.1 Background

"There is nothing permanent except change." The Greek philosopher Heraclitus probably did not have the environment in mind when he uttered these words more than 2500 years ago. Considering the current situation, however, one may wonder if ever there was a time when the environment was more subject to change. Since the dawn of time humans have used the earth's renewable resources to satisfy their needs. Humans were first hunters and gatherers; we then proceeded to become pastoralists and agriculturalists. Although this scenario has continued into the modern era as human society has become progressively industrialised and urbanised, agriculture is still essential to our survival.

Modern agriculture has meanwhile become increasingly unsustainable. The basic practices that form the backbone of modern agriculture are destroying the very foundation upon which it is built (Gliessman, 2007). Not only have we been degrading natural resources in the process, but the profit margins in agriculture are steadily declining. Input costs are soaring and many agrochemicals (especially the pesticides) have not only become less effective, but the costs have escalated enormously. With the increase in the global awareness of health-related risks associated with agrochemicals, the pressure is steadily mounting to force producers to resort to safer and more environmentally friendly cultivation methods. Adding pressure to the cause are the frequent food shortages which have resulted in political unrest in various parts of the world. Researchers and producers alike have indicated the need for more sustainable food production systems and growers now have more reason than ever for converting conventional, high-input production systems to more sustainable production systems.

1.2 Problem Statement

The main problem that was identified for this study related to the transition of conventional macadamia cultivation which depends heavily on agrochemicals, to more sustainable cultivation practices which are based on ecological principles. In conventional macadamia production systems, the external input of inorganic fertilizers circumvents the ecological processes of nutrient cycling, and the capture and release in soils and conventional crop protection practices in macadamia orchards depend largely on the application of synthetic agrochemicals which disrupt natural ecological processes and populations of both target and non-target species.

The transition poses significant challenges with its aim of creating a stable and resilient agroecosystem which still produces viably and cost-effectively despite the decrease in chemical input. Sustainable alternatives for crop nutrition and protection may be the two most difficult areas to find solutions for; the foundation of crop nutrition is the soil where the focus should be to optimize soil fertility and in a macadamia orchard, stinkbug damages equate to as much as 80 percent of the crop protection problem. Conversions in macadamia orchards should therefore commence in finding solutions to optimize soil fertility so that nutrient cycling and release may be optimized, and the ecological or other sustainable control of stinkbugs should be a priority in the search for sustainable solutions in crop protection.

1.3 Research Questions

i. How can soil fertility be optimized to enhance the ecological processes of nutrient cycling and release in macadamia orchards, this being one of the essential components of the conversion strategy, to achieve sustainability?

ii. In attempting to achieve the goal of a sustainable macadamia production agroecosystem, to what extent, and by which means, can ecological alternatives be implemented to control stinkbug pests in macadamia orchards?

1.4 Research Objectives

i. To investigate the potential use of cover crops and compost to enhance soil quality in macadamia orchards to convert from conventional macadamia cultivation systems to more sustainable methods.

ii. To investigate the potential use of cover crops and orchard heterogeneity to control stinkbug pests that target macadamia crops.

1.5 Research Aim

The main aim of the research was to contribute means for converting conventional, high-input production systems to more sustainable ecological systems, thereby improving the sustainability of macadamia production and ultimately contributing to food security.

1.6 Thesis Statement

Conventional cultivation practices can be substituted with alternative agroecological practices like the use of cover crops, biodiversity and compost, to improve soil quality, and to protect crops against stinkbug pests in macadamia orchards.

1.7 Motivation

The research aimed at finding means of improving soil quality with the aid of cover crops and compost; in turn this would enhance the ecological functioning of soils in terms of nutrient cycling, erosion resistance, and water retention. It would also improve physical and chemical properties of soil and create suitable habitats for soil organisms, which would impact positively on productivity and environmental quality (Lal, 2015). Ghaemi et al., (2014) indicate that soil quality is strongly linked to food security through numerous ecosystem services provided by soils. Robinson et al., (2011) advise that an ecosystems approach is important for soil science in the context of ecosystem services and soil change.

An increase in orchard biodiversity combined with associated trap crops could also create the potential for insect pest control. The principle of trap cropping is supported by the fact that virtually all pests show a distinct preference for certain plant species, cultivars, or certain crop stages. Manipulations of crop stands in time and space so that attractive alternative host plants are available at a critical time in the pest's and/or the crop's phenology, lead to the concentration of the pests away from the main crop towards the trap crop (Hokkanen, 1991). When biodiversity is increased with the aid of cover crops and natural vegetation in and around crop fields, biological control of insect pests is enhanced in three ways, i.e. more natural enemies of insect herbivores are present; alternative food sources for insect herbivores become available; and pest insects have more difficulty in locating preferred host plants in diverse environments as compared to monocultures (Altieri, 1989).

1.8 Delineation and Limitations

1.8.1 Delineation

The focus of this study was limited to investigating the use of cover crops, compost and orchard biodiversity to improve soil quality and to combat stinkbug pests in macadamia orchards.

1.8.2 Limitations

Time and funding prevented a whole-system conversion study which would have allowed for a better understanding of yield-limiting factors in the context of agroecosystem structure and function.

1.9 Definition of Terms and Concepts

Soil Health: *"those aspects of soil quality that reflects the condition of the soil as expressed by management-sensitive properties" (Islam and Weil, 2000). "The health of a soil refers not only to its lack of degradation or contamination, but also to its overall fitness for carrying out ecosystem functions and responding to environmental stresses" (Lewandowski, et al. 1999). This term is used interchangeably with soil quality and vice versa for this study and report.*

Soil Quality: *Doran et al., (1994) define soil quality as "the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health". This term is used interchangeably with soil health for this study and report.*

Active or Labile Carbon Content: *is a measure of the fraction of soil organic matter that is readily available as a carbon and energy source for the soil microbial community.*

Soil Organic Matter (SOM): *is any material that is derived from living organisms, including plants and soil fauna. Total soil organic matter consists of both living and dead material, including well decomposed humus.*

Potentially Mineralizable Nitrogen: *is the amount of nitrogen that is converted (mineralized) from an organic form to a plant-available inorganic form by the soil microbial community over seven days in an incubator. It* *is a measure of soil biological activity and an indicator of the amount of nitrogen that is rapidly available to the plant.*

Cover cropping: *is the practice of growing pure or mixed stands of annual or perennial herbaceous plants to cover the soil of croplands for part or all the year for the purpose of enhancing soil properties, biological pest control and for the enhancement of biodiversity within agroecosystems.*

Trap crops: *"plant stands grown to attract insects or other organisms like nematodes to protect target crops from pest attack, preventing the pests from reaching the crop or concentrating them in a certain part of the field where they can be economically destroyed" (Shelton and Badenes-Perez, 2006).*

Conventional agriculture: *refers to farming systems which rely heavily on external inputs such as agrochemicals and heavy irrigation to successfully produce on an economically viable basis. These systems are energy intensive but also highly productive.*

Monoculture: *is the agricultural practice of producing or growing a single crop or plant species over an area and for consecutive years.*

Polyculture: *is agriculture using multiple crops in the same space, in imitation of the diversity of natural ecosystems, and avoiding large stands of single crops, or monoculture. It includes multi-cropping, intercropping, companion planting, beneficial weeds, and alley cropping.*

Cultural cultivation practices: *are cultivation practices used to enhance crop and livestock health and prevent weed, pest or disease problems without the use of chemical substances.*

Phytophagous insects: *Herbivorous or plant-eating insects.*

Polyphagous insects: *Insects that feed on many kinds of plants; having many host plants.*

Semiochemicals: *A chemical emitted by a plant or animal that evokes a behavioural or physiological response in another organism.*

Food security: *"food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO) — essentially a technical concept.*

Food sovereignty: *is the primacy of people's and community's rights to food and food production, over trade concerns, and is embedded in larger questions of social justice and the rights of farmers and indigenous communities to control their own futures and make their own decisions — essentially a political concept.*

1.10 Underlying Assumptions

Environmental variables, such as the climate which may have influenced soil quality in addition to the treatments applied (cover crops and compost) for this research, as well as external factors which may have had an impact on stinkbug behaviour in addition to the trap crop and biodiversity treatments applied, were assumed to be insignificant for the purpose of this research project.

1.11 Significance of the Study

1.11.1 Background

Agroecological conversions aim to provide sustainable solutions for agricultural endeavours; two of the most important focus areas in the conversion process include crop nutrition and crop protection. Most organic solutions for crop nutrition are built on the foundation of a healthy growth medium or a high-quality soil. Soil organic matter enhances almost all characteristics related to healthy soils. Practices that promote good soil organic matter management are therefore the very foundation of high quality, healthy soils and consequentially result in a more sustainable and thriving agriculture (Magdoff and van Es, 2009). There is a renewed interest in cover crops and the role they can play in the pursuit of sustainability in agroecosystems. These versatile crops have not only demonstrated the ability to improve soil, but numerous species have also shown the potential to act as trap crops for insect pests.

Phytophagous stink bugs (Heteroptera: Pentatomidae) are important pests of many crops (including macadamia nuts), feeding mostly on seeds and immature fruits. During feeding they utilize their stylets to remove contents from the host plant cells. The resulting damage includes premature drop and/or malformation of seeds and fruits. As stink bugs are generally polyphagous, they feed on a variety of plants but show distinct preferences for certain plant species. Consequently, attractive host plants can potentially be offered to lure these pests away from the main crop.

1.10.2 Strategic Importance and Relevance

When agroecosystems are redesigned to achieve natural ecosystem-like characteristics by incorporating ecological processes, the root causes of many of the sustainability related problems are addressed and ecological sustainability may be achieved. Studies have shown that the conversions to agroecosystems improve the overall sustainability of most of these cropping systems that are converted (Benayas, and Bullock, 2012; Caporali and Campiglia, 2001; Evenari, et al., 1961; Fernandez et al., 2008; Gliessman et al., 1996; Letourneau et al., 2011; Pywell et al., 2011;

Reeve et. al., 2011; Swezey et al., 1994; 1998). Although sustainability may not yet have been fully achieved, agroecological conversions can increase components of sustainability. Farmers have also achieved organic certification and promoted awareness of alternative food systems, which have proved not only popular, but also profitable.

Various efforts have been made to grow macadamia nuts organically (Schoeman and Mohlala, 2007; Wilkinson, 2005; Seabrook, 2001). Recorded case studies have shown the attempts to grow macadamia nuts organically have been partially successful where some loss in yield and quality is accepted as part of the equation. No cases are known where macadamia orchard agroecosystems have been redesigned to function on sustainable ecological principles alone. Schoeman (2007) advises that a macadamia orchard with the related weeds, natural host plants as well as arthropod complexes, should ideally be managed as an ecological unit with the aim to make conditions for pests unfavourable, but at the same time rendering conditions for the cultivated host plant as optimal as possible.

South Africa currently ranks as the largest producer of macadamia nuts worldwide. Cultivating macadamias more sustainably, by aiming for organic conversions of macadamia production systems, will have a positive impact on the industry by opening access to the growing international market for organic produce. It will also benefit both commercial and small farmers by decreasing input costs and increasing long-term profitability. This is of strategic importance to the macadamia industry in the Vhembe region of Limpopo Province, since it would provide an entry mechanism for new small-scale commercial macadamia farmers who lack the capital or skills to establish the kind of high-input, intensively cultivated macadamia orchards characteristically found in the region. It would also increase labour absorption, in contrast to the progressive labour-shedding by the increasingly mechanised conventional macadamia production systems. In fact, economic spin-offs and impacts on unemployment and poverty alleviation will be significant as conventional practices have become increasingly unsustainable both economically and ecologically.

The South African Macadamia Growers' Association (SAMAC) has also identified small-scale macadamia farmers as a category of producers who urgently need training and assistance to enable them to cultivate macadamia nuts at economically viable levels. The most significant challenge these farmers face is to protect their macadamia crops from stinkbug pests. Chemical pest control is not only expensive, but difficult for small farmers to utilize as most of the pesticides that are registered for macadamia nuts need expensive equipment like mechanised mist blowers for effective application. Ecological solutions for protecting macadamia nuts in the circumstances under which these farmers operate, may therefore contribute significantly to sustainable livelihoods in rural Vhembe, considered to be one of the poorest districts of Limpopo Province. Agroecological approaches to farming could potentially also produce food free of potentially hazardous chemical residues, make it ecologically more sustainable, while producers are guaranteed a premium on organically cultivated products.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

Various attempts have been made to develop strategies for sustainable agriculture. The most common approach has probably been organic farming. Other strategies include biodynamic farming, biological farming (also known as nature farming) and permaculture. All these approaches aim to reduce dependence on inorganic agrochemicals to minimize adverse impacts on the environment. In reality, however, the strategies commonly advocated by most of these approaches only achieve a reduction in agrochemical input, but does not necessarily lead to the development of more self-sufficient and sustainable farming systems (Altieri et al., 2017). Agroecology is one of these advances which has developed as a way of conceptualizing the design and management of an agricultural system (agroecosystem) such that ecological concepts and principles are integrated with sustainability. In its several conceptions, it has emerged as a scientific approach used to study, diagnose and propose an alternative, low-input management of agroecosystems (Altieri, 1989). The primary aim of agroecology is therefore to solve the sustainability challenge of modern agriculture.

Gliessman (1998) traced the history of agroecology to the early part of the previous century when ecologists and agronomists found common ground, but it was only in the 1970s when literature began to appear on the subject. Agroecology has been variously defined as the ecology of agriculture, the study of ecological functions in farming, and the marriage of agriculture and ecology. Altieri (1989) loosely defines agroecology "as a more environmentally and socially sensitive approach to agriculture, one that focuses not only on production, but also on the ecological sustainability of the production system," but more specifically "to the study of purely ecological phenomena within the crop field, such as predator/prey relations, or crop/weed competition". Francis et al., (2003) presents a rationale for defining agroecology as "the ecology of food systems" where ecological, economic and social dimensions become a part of the equation. Gliessman (2015) in turn defined it as "the science of applying ecological concepts and principles to the design and management of sustainable food systems".

Mendez et al. (2016) concurs with Altieri (1987) that agroecology helps us to understand the ecology of traditional farming systems better and responds to the mounting problems resulting from increasingly globalised and industrialised agri-food systems. Unlike most other approaches which focus on singular components of the agroecosystem like organic farming which demands the exclusion of inorganic agrochemicals, agroecology highlights the interrelatedness of all agroecosystem components and the complex dynamics of ecological processes. Agroecology also endeavours to minimize dependence on external off-farm inputs. The approach here is rather to redesign agroecosystems so that they restore and sustain ecological interactions to provide the mechanisms for sponsoring soil fertility, productivity, and crop protection (Altieri et al., 2017).

Agroecology is now widely recognized internationally as an approach that may be practiced on par with other approaches such as biological and conservation farming, precision farming and integrated pest management, to address food security. Agroecology does however not need to be combined with other approaches. Without the need of intensive external input substitutions akin to commercial organic farming, it has increasingly and consistently proven capable of increasing productivity both at commercial and traditional levels and has demonstrated far greater potential for fighting poverty, particularly during economic and climatically uncertain times, which are becoming common worldwide (Altieri et al., 2017).

When an agroecosystem is referred to, it is generally considered equivalent to an individual farm, although it could just as easily be a single crop field, orchard or a grouping of adjacent farms (Gliessman, 2015). What is it that renders natural ecosystems sustainable over time? How do forests, grasslands and other ecosystems manage to sustain themselves indefinitely? The understanding of the fundamental processes in natural ecosystems becomes critical in successfully applying ecological principles to agroecosystems (Malézieux, 2012; Ratnadass et al., 2012). In agroecology, a crop field, orchard or farm is viewed as a cultivated ecosystem. The same ecological rules apply in an orchard or crop field; no amount of human interference or disturbance to the environment will eradicate the forces present in nature. This is evident when weeds appear from nowhere in our crop fields as succession sets about to repair the disturbances caused to ecosystems by cultivation practices. The challenge in creating sustainable agroecosystems is one of achieving natural ecosystem-like characteristics while maintaining a harvest output.

What is a sustainable agroecosystem? It is one that maintains the resource base upon which it depends, relies on a minimum of artificial inputs from outside the farm system, manages pests and diseases through internal regulating mechanisms, and can recover from the disturbances caused by cultivation and harvest (Altieri, 1989; Edwards et al., 1990; Dalsgaard et al., 1994; Gliessman, 2001;

Buchs, 2003). Agroecological management leads to natural ecosystem mechanisms manifesting in cultivated ecosystems and improving processes such as nutrient cycling, energy flows, water and soil conservation and pest–natural enemy populations within agroecosystems where these processes maintain productivity and self-sustaining capacity. Aligning modern agricultural systems with ecological principles is however complicated, especially in the current tendency in commercial agricultural to specialize and focus on short-term productivity and where economic efficiency has become the driving force (Gliessman, 2007; Moonen and Barberi, 2008; Altieri et al., 2017). It is important to understand the ecological processes to apply them successfully in agroecosystems. The main strategy of the agroecological approach is to apply these ecological concepts and principles to the design and management of agroecosystems. Pure organic conversions may solve all or most of the problems associated with conventional farming practices but will not necessarily prevent problems from arising in the first place (Gliessman, 2015).

2.2 Agroecological Conversions

Modern agriculture has replaced natural plant communities with cultivated monoculture crop communities. This has converted stable ecosystems into simplified plant communities which no longer have the ecological structure and functions needed to exist sustainably. Converting simplified systems to more sustainable agroecosystems can unfortunately not be achieved by only implementing practices like composting or cover cropping or even converting to organic farming, but rather from implementing well defined agroecological principles by using various practices and strategies, each applied with specific aim to achieve different effects on productivity, stability and resiliency of the agroecosystem. Conversions from simplified cultivation systems to diverse and sustainable agroecosystems attempt to imitate natural ecological processes leading to improved nutrient cycling and energy flow, efficient pest population regulating mechanisms through enhanced natural enemy populations and more effective water and soil conservation, combined with increased organic matter turnover, resulting in soil biological activation (Nicholls et al., 2016).

Altieri et al., (2017) maintain that agricultural intensification still presides over agroecological approaches to solve food security challenges. They point out that "Agroecology transcends the reformist notion of organic agriculture and sustainable intensification proponents who contend that changes can be achieved within the dominant agro-industrial system with minor adjustments or greening of the current neoliberal agricultural model".

Agroecological conversions are complex, requiring changes at all levels of the farming enterprise. Farmers not only have to make significant adjustments in the physical management of their farming operations but must also be able to make mental adjustments in their approach to conventional farming practises. As most successful farmers are usually innovative individuals who are used to problem solving because of the many challenges that they face daily, they are often good candidates for implementing changes in farming operations, should they perceive these changes as beneficial to their farming enterprises. Proper guidance is, however, essential for the successful outcome of agroecological conversions. These conversions are generally implemented step by step with three marked phases (Nicholls et al., 2016):

1. Increased efficiency of input use through integrated pest management or integrated soil fertility management.
2. Input substitution using environmentally benign inputs (botanical or microbial pesticides, bio-fertilizers, etc.).
3. System redesign or diversification through optimal crop/animal assemblages which encourage interactions that allow the agroecosystem to sponsor its own soil fertility, natural pest control, and crop productivity (Nicholls et al., 2016).

Gliessman (2015) provided guiding principles for ecological conversions where the conversion process is systematically applied at five levels:
Level one is similar to what all good farmers usually practise, where the efficiencies of conventional practises are increased and the consumption of costly, scarce, or environmentally damaging inputs are reduced. At this level farmers will, for example, irrigate and fertilize a crop based on the measured needs of the plants and environmental conditions and not blindly apply standard irrigation or fertilization programmes. Precision farming is an example of a level one conversion.

Level two conversions start to substitute conventional inputs and practises with alternative, more sustainable practises. The aim is to replace resource-intensive and environmentally-degrading practises with those that are more environmentally friendly. These are usually, but not necessarily, organic conversions.

Level three commences when most of the unsustainable conventional practises have been replaced with sustainable alternatives. The agroecosystem i.e. the crop field, orchard or farm is now being redesigned to function based on ecological processes. Ecological processes, like energy flow, diversity and nutrient cycling are enhanced to improve the stability and resilience of the agroecosystem. Most importantly now, the root causes of many ecosystem related problems can be addressed instead of only treating the symptoms, which are so characteristic of conventional farming operations.

The fourth level aims to re-establish a more direct connection between those who grow the food and those who consume it. The context is predominantly a cultural and economic one. Traceability, locally produced and consumed produce and transformation within commercial and small farmer producers, become important issues and labour relations and labour ethics are addressed with the aim of creating sustainable working conditions for farm workers at all levels. Finally, level five progresses to a level where there is a contribution to building a new global food system, based on equity, participation and justice, that is not only sustainable but also helps restore and protect earth's life-support systems.

Level five now moves beyond food security to address food sovereignty where people and communities' rights to food and food production is given primacy over trade concerns and is embedded in larger questions of social justice, where the right of farmers and indigenous communities to control their own futures is acknowledged.

Two of the main challenges of level two conversions in crop production relate to the nutrition and protection of the crop plant. Nicholls and Altieri (2004) suggest that ecosystems become productive when a balance of rich growing conditions prevail that allow crops to become strong and healthy, which in turn render them resilient to stress and adversity. One of the most important strategies to improve and maintain these conditions in most soils is to incorporate organic matter in the soil. Sustainable organic solutions for crop protection, on the other hand, are based on an array of cultural and biological management strategies. These must cater for pests, diseases and adverse environmental conditions, which may affect plant survival and quality. Fruit trees are susceptible to attacks by a wide spectrum of insects at all stages of their growth just like any other crop. Virtually all herbivore insect pests, however, show distinct preferences for certain plant species, cultivars, or certain crop stages (Hokkanen, 1991). Attractive alternative host plants can, therefore, potentially be used to lure pests away from the main crop to the more attractive host plants, commonly called trap crops. Cover crops could serve both the purposes of promoting soil organic management and of trap crops for some insect pests depending on the choice and application thereof.

2.3 Soil Quality

Enhancing soil quality in intensive agricultural systems is important for sustained productivity and improving environmental quality (Subbian et al., 2000). High quality soils are synonymous with rich growing conditions for plants and are therefore *per se* worth quantifying, because soils and their biota provide valuable ecosystem services, like storing and releasing water, decomposing plant and animal matter, transforming and recycling nutrients, sequestering and detoxifying toxicants, and promoting plant health by suppressing plant-pathogenic microbes and phytophagous fauna (Doran and Zeiss, 2000). Soil quality deals with the integration and optimization of the physical, chemical and biological properties of soil for improved productivity and environmental quality (Karlen et al., 2001). When soil quality parameters are in the optimum range, crop yield would be optimal (i.e., maximum obtainable yield) with reduced soil degradation (Ghaemi et al., 2014).

Doran et al., (1994) define soil quality as “the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health”.

2.3.1 Soil Quality Indicators

Many authors have attempted to develop soil quality (or health) indicators by measuring various soil characteristics (Arshad and Martin, 2002; Doran and Zeiss, 2000; Glover et al., 2000; Gugino et al., 2009; Karlen et al., 2003; 2008; Knoepp et al., 2000; van Antwerpen, 2009; van Bruggen and Semenov, 2000; Werner, 1997; Ghaemi et al., 2014). Indicators of soil quality for agroecosystems are described by many different variables that include mainly chemical, physical and biological parameters (Mele and Crowley, 2008). These indicators refer to measurable soil attributes that influence the capacity of soil to sustain crop production or environmental functions (Arshad and Martin, 2002) and which reveal trends in soil quality to be constant, declining or improving (Ghaemi et al., 2014). The choice of a standard set of specific properties as indicators of soil quality can be complex and will vary among agroecosystems and management objectives (Schoenholtz et al., 2000). Most chemical and physical property variables that are relevant to soil quality are well understood, consequently their various indices, as developed by researchers and practitioners, are largely similar in principle and content. Biological properties, however, have been much more difficult to use as tools for monitoring soil quality: there are no standard reference values that can be used for comparisons over time and across different management systems. The concept of soil quality seems to be clear, but measuring it remains difficult (Zornoza et al., 2007).

As modern agriculture is developing towards low input systems where soil biological processes primarily account for soil fertility, nutrient cycling, and disease control, key indicators of soil quality must include biological measures. Biological indicators have consequently become increasingly important in the assessment of quality in soils that are managed mainly to enhance their ecological functioning (Neilsen and Winding, 2002). Ghaemi et al., (2014) emphasise physical quality which includes the soil structure that would reduce erosion and compaction if it is stable and provide favourable conditions for plant growth. They measure soil physical quality by measuring indicators such as air capacity, available water holding capacity, relative field capacity to water saturation, macro-porosity, bulk density, soil organic carbon and aggregate stability, among others.

Any one method for characterizing microbial community structure and function provides only a limited perspective on soil biological responses to different environmental variables. Soil quality must be inferred from easily measurable soil properties and these soil quality indicators must be comprehensible, and useful to land managers, who are the ultimate stewards of soil quality and health (Acton and Padbury, 1993; Doran and Zeis, 2000). Kremer and Hezel (2012) describe soil quality assessment as the ability of management systems to optimize soil productivity and to maintain its structural and biological integrity.

Magdoff and Weil (2004) point out that researchers have found soil organic matter (SOM) related properties to be important indicators of soil quality. Dumansky (1994) concluded that "soil organic matter is emerging as a key indicator for assessing sustainability" of land management systems. SOM management is the key for not only converting degraded or low-quality soils into high quality ones, but also for maintaining or improving already healthy soils (Magdoff and van Es, 2009).

Which soil quality indicators are most likely to be affected using cover crops and applications of organic material? Soil quality indices and indicators should be selected according to the soil functions of interest and the defined management goals for the system (Andrews et al., 2002). Indicators for any study should, therefore, firstly, be selected to best reflect the achievement of the goals identified and secondly to meet the criteria proposed by Doran and Zeiss (2000), which are: a sensitivity to variations in management and good correlation with beneficial soil functions; useful for elucidating ecosystem processes; comprehensible and useful to land managers and easy and inexpensive to measure. Some researches (Ghaemi et al., 2014) have developed indices such as a sustainability index which not only measures threshold values of important soil indicators, but have rating functions based on crop production limitations and provide an indication of the sustainability of soil ecosystems in terms of soil degradation. Gugino et al. (2009) developed a protocol for assessing the health status of soils. They evaluated 39 potential indicators for their use in rapidly assessing soil health based on:

- Sensitivity to changes in the soil
- Management practices
- Relevance to soil processes and functions
- Consistency and reproducibility
- Ease and cost of sampling
- Cost of analysis

This protocol (also known as the Cornell soil health assessment protocol) emphasizes the integration of soil biological measurements with soil physical and chemical measurements. A total of 4 physical and 4 biological indicators with a standard chemical soil test analysis were selected for the protocol. This protocol conforms well to the criteria proposed by Doran and Zeiss (2000).

2.4 Soil Organic Matter

Some of the most significant ecological processes in crop production are those occurring within the soil, namely the interactions between soil, nutrients and micro-organisms. The normal functioning of these processes is essential for healthy crop growth and sustainable production. Good soil organic matter management is the foundation for creating a favourable environment for the proper functioning of these ecological processes in the soil. The soil organic carbon (SOC) is a key indicator of soil quality and an important driver of agricultural sustainability. Anything that adds large amounts of organic residues to a soil may increase organic matter (Kimetu et al., 2008; Lal, 2015). Quantity of SOC in the soil, it's depth distribution and other qualities have a significant impact on physical qualities of soil, such as soil structure, water availability for plants, rooting depth and soil temperatures. Likewise, the biological quality is positively impacted and chemical qualities like pH and nutrient availability also improve significantly with the increase of SOC (Lal, 2015). One of the oldest practices in agriculture has been to apply manures or other organic residues generated off the field. A typical agricultural soil has 1 to 6 per cent organic matter, which consists of three distinctly different parts: living organisms, fresh residues like compost, and well-decomposed residues called humus (Magdoff and van Es, 2009). Humic substances play a vital role in soil fertility and plant nutrition and are involved in soil structure, porosity, water holding capacity, cation and anion exchange, and the chelation of mineral elements (Pettit, 2004). The availability of nutrients is influenced, either directly or indirectly, by the presence of humus and humic substances. The intimate contact of humus with the other soil components allows many reactions, such as the release of available nutrients into the soil water, to occur rapidly (Seiter and Horwath, 2004).

Most of the nutrients in soil organic matter cannot be used by plants if they exist as part of large organic molecules. Soil organisms are positively correlated with organic matter content (Nair and Ngouajio, 2012). As soil organisms decompose organic matter, nutrients are converted into simpler inorganic or mineral forms that plants can easily use. This process, called mineralization, provides much of the nitrogen that plants need. Soil organisms are therefore essential for keeping plants well supplied with nutrients, because they make nutrients available by freeing them from organic molecules (Hulugalle et al., 1999; Anderson, 2003; Doran and Zeiss, 2000). For example, proteins are converted to ammonium (NH_4^+) and then to nitrate (NO_3^-). The mineralization of organic matter is also an important mechanism for supplying plants with such nutrients as phosphorous and sulphur, and most of the micronutrients they need (Magdoff and van Es, 2009).

Soil organisms contribute significantly to soil quality and is essential to restoring and improving soil quality (Lal, 2015) and are essential for keeping plants well supplied with nutrients because of the role that they play in breaking down and processing organic matter (Hulugalle et al., 1999; Doran and Zeiss, 2000; Anderson, 2003). When organic matter is broken down by microorganisms, compounds are formed which help bind together soil particles as aggregates. Soil aggregation stability is a measure of the extent to which soil aggregates resist disintegrating when wetted and hit by rain drops (Gugino et al., 2009). Well aggregated soils till easily, are well aerated and have high water infiltration rates (Sullivan, 2003). If soil organisms are absent or inactive, more fertilizers will be needed to supply plant nutrients. Soil organisms are highly dependent on soil organic matter as source of food, and humic substances are a particularly good source of energy for beneficial organisms. Organic matter, as residue on the soil surface or as a binding agent for aggregates near the surface, also plays an important role in decreasing soil erosion. Organic matter content is also the single most important soil property that reduces pesticide leaching as it can change the chemical structure of some pesticides, and other potentially toxic chemicals, rendering them harmless. It also impacts the rate of surface applied herbicides along with soil pH necessary to control weeds effectively. A supply of active organic matter must therefore be maintained so that humus can continually accumulate (Magdoff and van Es, 2009, Snapp and Grandy, 2011, USDA-NRCS, 2014).

2.5 Cover Crops

There is a renewed interest in cover crops and the role that they can play in increasing SOM. These versatile crops can improve soil in various ways. Cover crops have the potential to help maintain diversity below the ground where they are growing, and they can return residues to the soil when they are mulched or green manured (Hulugalle et al., 1999; Clark, 2007; Jokela et al., 2009). 'Green manuring' involves the incorporation in the soil of any field or forage crop while green or soon after flowering, for soil improvement. Some cover crops may produce 2 to 3 tons of biomass per hectare under optimal conditions. This biomass becomes an important supply of organic matter where other sources may be limited. Commercial agriculture can rarely afford regular applications of large quantities of organic material; this is especially true of semi-arid regions like southern Africa, where a relatively low rainfall limits the availability of plant material which can be composted for this purpose. Biomass production through cover crops for composting purposes is, however, relatively cheap compared to other sources like animal manure and commercial compost.

Cover crops can provide numerous ecosystem services (Silva and Moore, 2016), such as improving soil quality, nutrient cycling, insect pest regulation and also supply nutrients to the follow-up crop (Sullivan, 2003). Nitrogen production from legumes is a key benefit of cover crops and 40% to 60% is usually available to a following crop (Silva and Moore, 2016). In addition, cover crops also help recycle other nutrients on the farm. These nutrients are accumulated by cover crops during the growing season and later become available during decomposition of the cover crops after green-manuring or mulching them. Cover crops provide direct competition for weeds (Mennan and Ngouajio, 2012, Silva and Moore, 2016), when they shade the soil, limit growing space and compete for water and nutrients and are strategically important in sequestering carbon in soils of agroecosystems (Lal, 2011). De Lima et al., (2012) found the use of cover crops to affect the support capacity of soil and least limiting water range to crop growth positively. McDaniel et al., (2014) consider cover crops to sustain soil quality and productivity by enhancing soil C, N, and microbial biomass, making them a cornerstone for sustainable agroecosystems. Most studies show that cover crops have a significant influence on SOM characteristics (Ding et al., 2006; Kimetu et al., 2008; Lal, 2011; McDaniel et al., 2014; Nascente et al., 2013; Steenwerth and Belina, 2008a). The addition of organic matter to the soil from cover crops to build SOM is a major benefit (Ding et al., 2006; Clark, 2007; Steenwerth and Belina, 2008b, Snapp and Grandy, 2011). Legumes are a popular choice as cover crops for the added benefit of nitrogen fixation.

Cover crops can also play a role in crop protection. Bugg et al., (2009) found understory cover crops in pecan orchards to enhance some arthropods that may aid the biological control of pecan pests. Pest cycles are broken when cover crops are non-hosts for these pests. Furthermore, cover crops may act as 'trap crops' to lure pests away from the main crop or create a favourable environment for more diverse insect populations which may harbour beneficial insects like pollinators and predators (Silva and Moore, 2016). Silva et al., (2010) found significantly higher numbers of beneficial arthropods in orchards with ground cover vegetation in comparison with bare soil. Cover crops help maintain high populations of mycorrhizal fungal spores, which help improve inoculation of the next crop and can affect the functional diversity of soil microbial communities (Nair and Ngouajio, 2012) Their pollen and nectar are important food sources for predatory mites and parasitic wasps, both important for biological control of insect pests. Cover crops have the important function of adding diversity to cropping systems. Herbivore insect pests find host plants easier in monocultures than in more diverse polycultures. Cover crops provide good habitats for spiders, and these general feeders help decrease pest populations (Magdoff and van Es, 2009; Ramos et al., 2010). Some researchers consider cover crops to be the backbone of any annual cropping system that seeks to be sustainable (Sullivan, 2003). Schipanski et al., (2013) estimated that cover crops could increase 8 of the 11 ecosystem services they investigated without negatively influencing crop yields. Cover crops increased almost all supporting and regulating services, including biomass production, nitrogen supply, soil carbon storage, nitrate retention, erosion control, weed suppression, mycorrhizal colonization, and beneficial insect conservation. The exceptions were insect pest suppression and nitrous oxide reduction, which were not different or decreased, respectively, in the cover crop treatments.

2.6 Trap Crops

Habitat and vegetation management can be used effectively as the basis for ecologically based pest management tactics in sustainable agriculture (Andow, 1991; Altieri and Letourneau, 1984;

Bukovinsky and van Lenteren, 2007; Gurr et al., 2003; Hendrickx et al., 2007; Letourneau et al., 2011; Pickett and Bugg, 1998; Proveda et al., 2008; Schoeman, 2007; Schoeman and Mohlala, 2007). The concept of trap cropping fits into the ecological framework of habitat manipulation of an agroecosystem for pest management (Altieri and Nicholls, 2005). Phytophagous hemipterans are, in general, polyphagous. They may however, show feeding preferences for certain taxa (Panizzi, 2000) which may produce different chemicals or volatiles that attract or repel insects (Wszelaki and Broughton, 2013). Plants that are highly attractive to these insects, therefore, have the potential to be used as trap crops. Various trap crops have been recorded to attract pentatomid stink bugs (Knight and Gurr, 2006; Lockwood and Story, 1986; Mizell et al., 2008; Shelton and Badenes-Perez, 2006; Velasco et al., 1995; Velasco and Walter, 1992; 2001, Holden et al., 2012). When trap crops successfully attract pest populations, damage to the main crops is limited, saving on the cost of applying pesticides; this may allow the cultivation of crops which would otherwise not have been economically viable (Wszelaki and Broughton, 2013). Shelton and Badenes-Perez (2006) believe the potential of trap cropping may be significant if farmers, scientists and extension educators could expand their concepts of trap cropping to include more diverse modalities in their research, which should include those based on the trap crop plant *per se*, modalities based on the deployment of the trap crop and others like biological control-assisted trap cropping and semiochemically assisted trap cropping.

2.7.1 Trap Cropping Systems

The potential success of a trap cropping system depends on the interaction of the characteristics and deployment of the trap crop with the ecology and behaviour of the targeted insect pest (Shelton and Badenes-Perez, 2006). In general, the attractiveness of the trap crop and the presentation of trap crops in the field are important factors in attracting the insects and in the success of the trap cropping system (Velasco and Walter, 1992). Finding a trap crop that the pest distinctly prefers over the main crop appears to be crucial for developing efficient trap crop systems (Hannunen, 2005).

2.7.2 Trap Crops and Biodiversity

Various researchers have demonstrated the potential of increased biodiversity to enhance biological control of insect pests in agroecosystems. Pest herbivore suppression and natural enemy densities were significantly improved on diversified crops compared to monocultures and this resulted in less crop damage (Altieri and Letourneau, 1984; Andow, 1991, Gurr et al., 2003; Bianchi et al., 2006; Poveda et al., 2008; Letourneau et al., 2011, Parker et al., 2016). Ecosystem function often improves with an increase in species diversity. In agricultural fields this not only happens when trap crops lure pests away from the main crop, but polycultures which increase habitat heterogeneity provide the pests' natural enemies with a more diverse resource base (Parker et al., 2016). Landis et al. (2000) and Philpot (2013), however, caution that to selectively enhance natural enemies, the important elements of diversity should be identified and provided rather than simply increasing diversity *per se,* which can exacerbate some pest problems. This can be achieved by improving the natural resources needed by natural enemies through the provision of a suitable habitat with adequate shelter, more suitable microclimates as well as alternative food sources such as pollen and nectar which may also benefit other beneficial insects like pollinators. The challenge is to integrate these resources into the landscape in a way that is spatially and temporally favourable to natural enemies and practical for producers to implement. Such a design to increase biodiversity may include other vegetation and livestock in addition to crop plants as well as all other organisms in the agroecosystem and surrounding landscape (Philpott, 2013). Biological process which renew natural ecological processes like nutrient recycling, control of microclimate, regulation of local hydrological processes, regulation of the abundance of undesirable organisms, and detoxification of noxious chemicals, are aided by biodiversity. The low level of biodiversity in modern agricultural systems is a concern for agroecologists. Allen (2013) demonstrated that the associated loss of habitat diversity in monocultures have created agroecosystem instability. Diverse plantings provide many benefits for agroecosystem health (Parker et al., 2016).

Habitat manipulation for the inclusion of trap crops may be made more effective by the simultaneous increase of biodiversity within and adjacent to the main crops. Altieri and Nicholls (2004) reviewed the influence of adjacent habitats on insect populations in crop fields. They concluded that these edges provide habitats for natural enemies which may choose to move back and forth from the edge to the crops for feeding. Morandin and Kremen (2013) found hedgerow restoration adjacent to crop fields to promote pollinator populations. Conservation of pollinator habitats may also render other ecosystem services like pest population reduction and protection of soil and water quality (Wratten et al., 2012). Perennial vegetation in strategic locations within agricultural landscapes have the potential to create opportunities for enhancing the control of pest and pathogen populations (Asbjornsen et al., 2013).

Gurr et al., (2004) view orchards as having a high potential for ecological engineering with regard to for pest management. They suggest that orchards are usually more diverse because of some type of ground cover and are subject to lower levels of disturbance than annual crops, and therefore have a greater potential for this type of management. The endeavour should be to manage orchard groundcover and adjacent vegetation toward enhancing the opportunity for biological control of orchard pests by natural enemies (Prokopy, 1994). The understory vegetation in an orchard need not be managed uniformly (Bugg et al., 1994). Different zones may be treated differently, which is called strip management. Various options include sowing cover crops of different floristic composition in different strips or combining it with strips of natural vegetation in or adjacent to the orchards. A complex of stands having different floristic compositions could remain attractive to arthropods for longer periods of time. Arthropod predator habitat can be retained through time with the aid of strip management combined with adjacent natural edges.

2.8 Knowledge Gaps and Research Needs

Gliessman (2015) maintains that there is an urgent need for more research on the sustainability of agroecosystems. Wezel et al., (2013) distinguished 15 categories of agroecological practices of which only 6 are currently well integrated in practices for sustainable agriculture. Asbjornsen (2013) identified the integration of perennial vegetation into agroecosystems for enhancing pest and pathogen population control as a critical gap in knowledge. One of the gaps which also needs to be addressed relates to the transition of conventional sub-tropical fruit cultivation, which depends heavily on agrochemicals, to more sustainable cultivation practices which are based on ecological principles. Conventional crop protection practices in fruit orchards that depend largely on the application of synthetic agrochemicals similarly disrupt natural ecological processes and populations of both target and non-target species. The potential of cover crops to build soil quality have been well documented (De Baets et al., 2011; Clark. 2007; Fatokun et al., 2002; Hubbard et al., 2013; Magdoff and van Es, 2009; Munoz-Carpena et al., 2008; Ramos et al., 2010; Seiter and Horwath, 2004; Singh et al., 2010; Snapp et al., 2006; Wang et al., 2011). Various cover crops have also demonstrated their potential as trap crops for various insect pests as well as promoting an increase in natural enemies (Agboka et al., 2013; Bone et al., 2009; Hinds and Hooks, 2013; Hokkanen, 1991); some have proven to be highly attractive to pentatomid stinkbugs (Knight and Gurr, 2007; Mizell, 2008; Mizell et al., 2008; Rea et al., 2002; Shelton and Badenes-Perez, 2006).

The question is whether cover crops could be deployed within sub-tropical fruit orchards in such a way that a dual goal is achieved. Could cover crops be utilized in sub-tropical fruit orchards to restore or maintain soil quality and simultaneously act as trap crops to reduce insect damage to sub-tropical fruit crops significantly? There is a need to investigate cover crops or combinations thereof which have already proven to be good soil builders, but also to have the potential to concurrently act as trap crops for pentatomid pest insects in sub-tropical fruit cropping systems. Mustard (*Brassica* spp.), Sunnhemp (*Crotolaria juncea*) and Cowpea (*Vigna unguiculata*) have all been identified as crops which all have twofold potential in this regard (Bensen and Temple, 2008; Bugg and Waddington, 1994; Fischler et al., 1999; Rea et al., 2002; Shelton and Badenes-Perez, 2006; Yost and Evans, 1988).

2.9 Conclusion

The principles on which sustainability can be built are well established, but we lack the more detailed knowledge needed to apply these principles to the design of sustainable systems and the global conversion of agriculture to sustainability. Cover crops may contribute significantly to this cause if their correct combination, application and management can be determined within given circumstances of sub-tropical fruit cropping systems. Where the latter occur in developing countries facing resource constraints, the optimal configuration of cover and trap crops has the potential to significantly reduce external farm inputs, prevent disruption of natural ecosystem processes and improve agricultural sustainability. Steyn et al. (2014) proposed that mustard (*Brassica* spp.), sunnhemp (*Crotolaria juncea*) and cowpea (*Vigna unguiculata*) be investigated in sub-tropical fruit cropping agroecosystems to determine their potential in this regard. I postulate that organic conversions which are mediated by the application of supplementary crops aimed to serve a dual trap and cover crop purpose, may achieve the goal of ecosystem conformity in sub-tropical fruit orchards more rapidly than conventional organic conversions which often attempt to convert to organic practices too hastily ("cold turkey" conversions) with resulting unstable and fragile agroecosystems that not only produce poorly but take long to recover some form of stability and resilience.

DATA CHAPTER ONE: PHASE ONE FIELD TRIALS

1.1 Introduction

The research was conducted by making use of field experiments to assess the potential of six cover crops to improve soil quality and, secondly, to simultaneously act as trap crops for stinkbug pests in macadamia orchards. Field experiments were selected as research tool because of their high replicability and treatments were replicated sufficiently to meet statistical requirements for adequate representation.

Field experiments were conducted in three phases: phase one tested the potential of six cover crops for crop protection (as trap crops) and simultaneously for soil restoration or fertility enhancement purposes in macadamia orchards. Phase two repeated the trials of phase one (both soil restoration and trap crops) but with modifications to both categories. The third phase repeated the trap crop trials only, but this time on three different study areas (all commercial farms) with the single cover crop which performed the best as a trap crop during phase two. Diversity of natural orchard vegetation was also enhanced in phase three to improve conditions for natural predators as part of the treatments in the last phase. Trials were modified from the first to the last phase to overcome practical implementation problems encountered along the way and to adapt to local conditions experienced in the commercial macadamia farming systems which served as research sites.

1.2 Materials and Methods

1.2.1 Experimental Design

The following cover crops were cultivated on experimental plots in macadamia orchards for the first phase of the field experiments, conducted on a commercial farm (Portion 28 of Welgevonden) 18km east of Louis Trichardt, Limpopo Province (Figure 1) in 2010: Mustard (*Brassica hirta* and *Brassica juncea* mixture), Buckwheat (*Fagopyrum esculentum*), Okra (*Abelmoschus esculentus*), Sunnhemp (*Crotolaria juncea*), Red Clover (*Trifolium pratense*) and Cowpea (*Vigna unguiculata*). These cover crops cultivated for the first phase were planted under the canopy of macadamia trees (Figures 2 and 3). The reason for this was that the study involved an investigation of the potential of cover crops to maintain or improve soil quality and the target area of soil improvement focussed mainly on the surface area below the canopy of the macadamia trees where most of the macadamia tree roots are located.

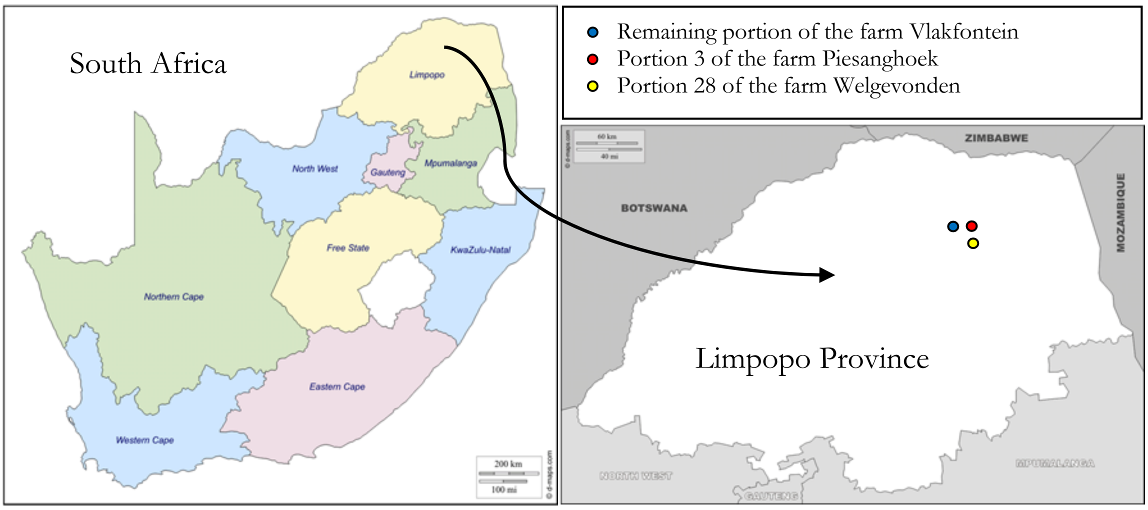


Figure 1. Study area and field trial sites within Limpopo Province, South Africa

A randomized complete block design was used for phase one, with each treatment located randomly within each block replicate (Figure 5). Blocks were replicated three times and selected to be as homogeneous as far as possible. Each replicate block contained twelve plots, representing the six crops to be tested as well as the control plot. Each plot in turn contained the main macadamia crop surrounded by rows of a mixed cover crop treatment applied as a strip crop under the tree canopy (Figures 2, 3). All plots were 16 m x 16 m (256 m^2) in size containing 3 rows of 5 macadamia trees each (Figure 4). The experimental plots were in orchards consisting of the same macadamia variety (695 Beaumont: *Macadamia tetraphylla x integrifolia*) in their seventh growing season, planted in rows of 8m x 4m spacing (Figure 4). Cover crops were cultivated on zero tillage principles to avoid additional impacts on macadamia tree roots and soil ecosystems; a drill seed planter was used to plant these in the orchards. Cover crops were mowed at maturity and their above-ground biomass spread in each respective plot as mulching under the tree canopies. Homma et al., (2012) found mechanical, mowing instead of herbicides in orchards, where the mowed weeds were spread under tree canopies, to have a reduced impact on the agroecosystem, mainly as regards biological processes. Soil samples were collected from within these trial plots where the cover crops were cultivated as soon as the cover crops reached maturity (flowering and seed production) and analysed to monitor and compare changes in the soil. All the cover crops were also tested for their ability to act as trap crops for stinkbugs in the study area.

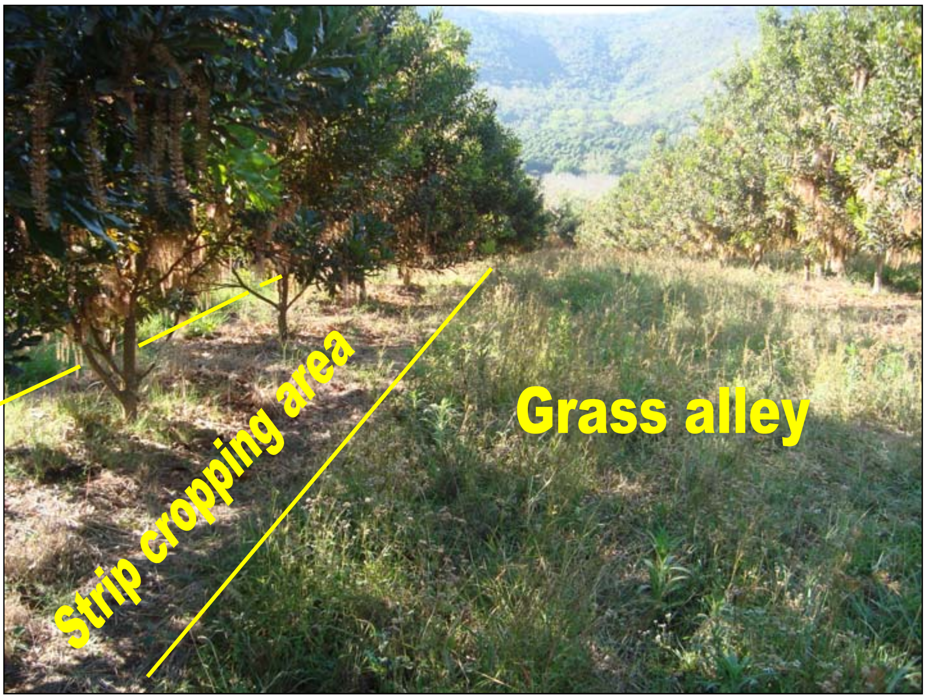


Figure 2. Trial plot indicating the strip cropping area earmarked for cover crops prior to cultivation in phase one.

Figure 3. Various cover crops cultivated under the tree canopies for phase 1.

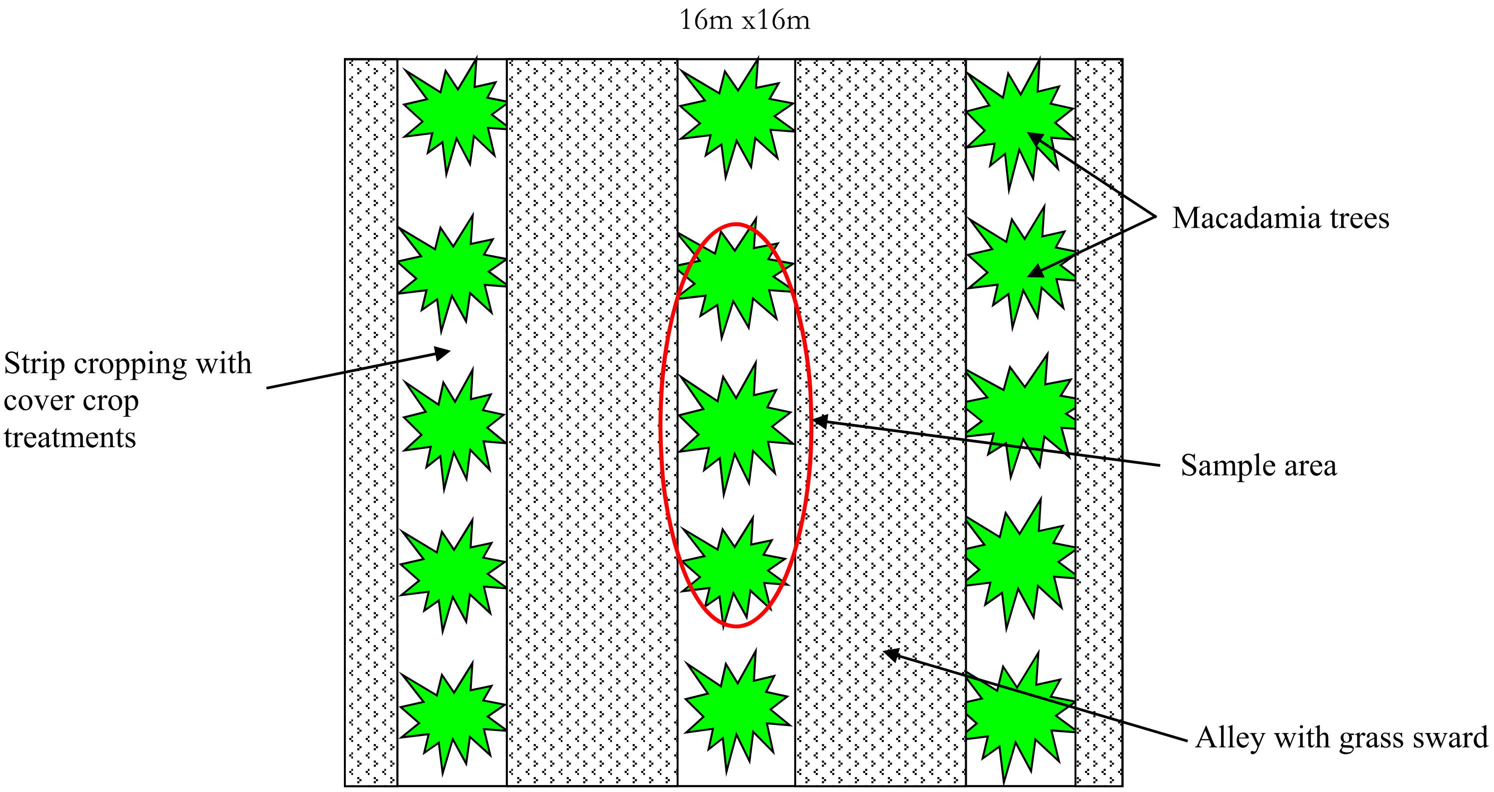
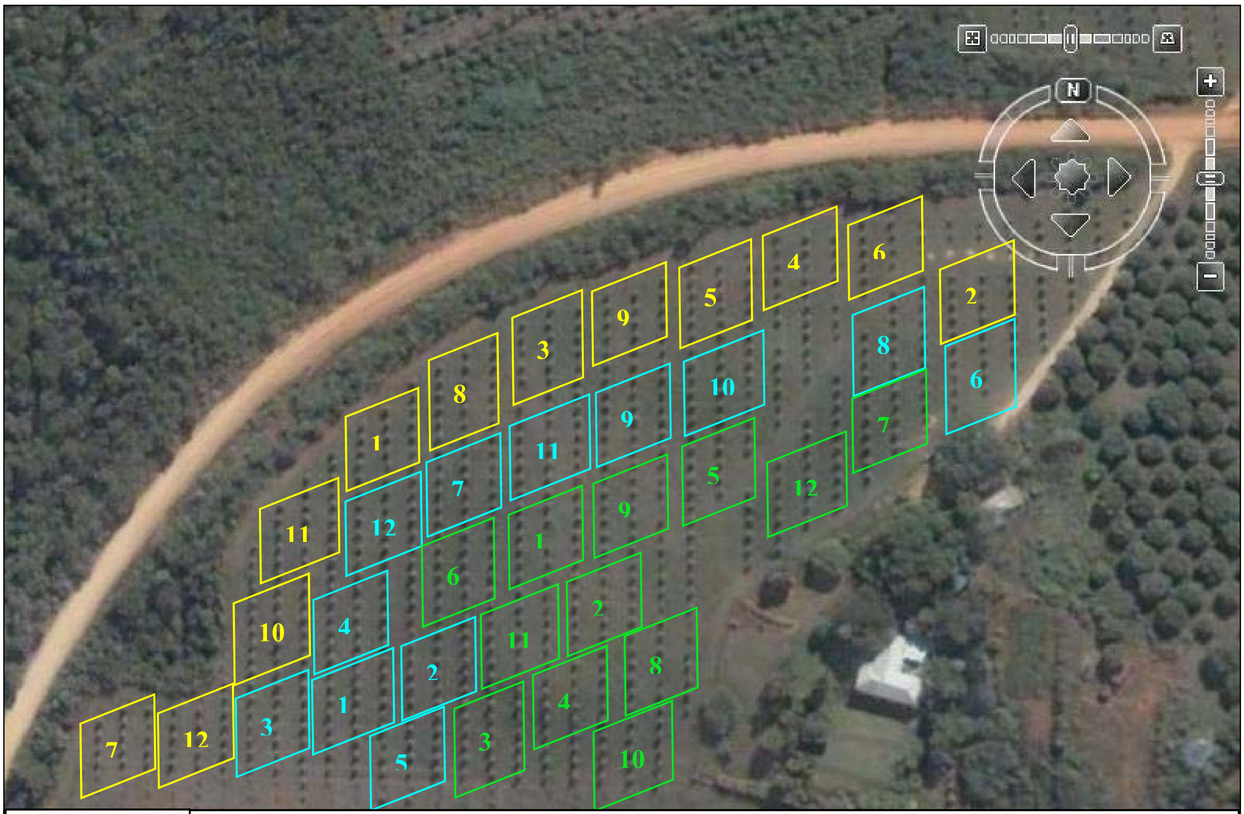


Figure 4. Experimental plot layout for phase one



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1 = cowpea x okra
2 = cowpea x red clover
3 = cowpea x mustard
4 = cowpea x buckwheat
5 = cowpea x sunnhemp
6 = sunnhemp x okra
7 = sunnhemp x red clover
8 = sunnhemp x mustard
9 = sunnhemp x buckwheat
10 = cowpea
11 = sunnhemp
12 = control

Figure 5. Block design indicating the randomized positions of 12 treatments replicated 3 times on portion 28 of the farm Welgevonden (Figure 1: locality map).

1.2.2 Stinkbug Sampling Procedures

Stink bug presence in trap crops and macadamia trees were recorded in phase one by making use of a standard mechanical knock-down technique or beating (Sutherland, 1996) on a weekly basis (twice per week). Data collection with this technique took place early morning before temperatures rose above 18°C (where possible) as stinkbugs are sensitive to sound and movement and tend to take flight when disturbed but are unable to do so when temperatures are below 18°C. These data were collected from October 2010 to February 2011.

1.3 Results and Discussion

1.3.1 Soil Quality Trials

The main purpose of phase one was to eliminate poor cover crop performers from the study and test the feasibility of cultivating them under the tree canopies. Preliminary soil analyses from the trial plots located under the tree canopies of two cover crop treatments, revealed that cultivating cover crops under the main crop canopy and within its root zone yielded negative results. Table 1 contains the results of the analysis of these soil samples showing how the cover crops (sunnhemp and cowpea sampled) competed with the main crop when it was cultivated under the tree canopy by extracting nutrients from the macadamia root zones. Notably the mean values of some macro elements like phosphorus (P) and potassium (K) as well as micro elements like zinc (Zn) decreased in the presence of cover crops; there was an even more significant decrease in exchangeable cations (Na, K, Ca and Mg). The cover crops also grew poorly under the canopy of the macadamia trees because of too much shade (Figure 6).

Table 1. Phase one soil analysis results (Bemlab soil lab: SANAS accreditation no: T0475)

	Resist.	H^+	P Bray II	K	Exchangeable cations (cmol(+)/kg)				Cu	Zn	Mn	B	Fe
	(Ohm)	(cmol/kg)	mg/kg		Na	K	Ca	Mg	mg/kg				
Control	930	0.44	14	682	0.12	1.74	11.9	5.2	38	9.5	702	0.16	196
Sunnhemp	1450	0.3	4	615	0.06	1.57	9.12	2.85	62	6.4	721	0.16	137
Cowpea	1790	0.79	3	505	0.05	1.29	7.71	3.05	48	7.8	854	0.3	271

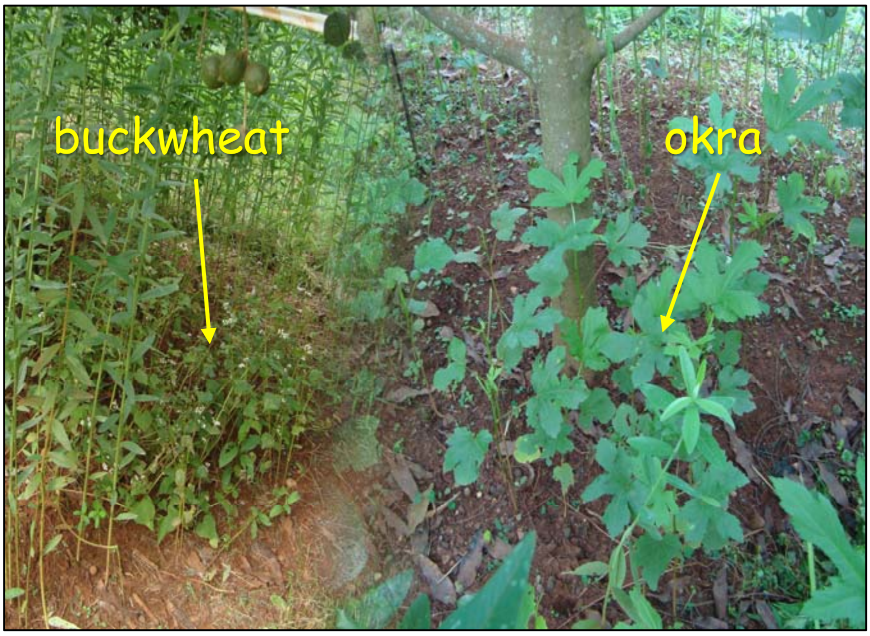


Figure 6. Buckwheat and okra growing poorly as result of too much shade.

1.3.2 Trap Crop Trials

Sunnhemp, cowpea and mustard displayed high potential as trap crops in the first round of trials especially for the three *Nezara* stinkbug species commonly found in the study area (Figure 7). Unfortunately, none of the cover crops had the ability to attract the two-spotted stinkbug i.e. *Bathycoelia natalicola* in large numbers like was the case with the *Nezara* species. The few specimens of this species found on the cover crops seemed to be there by chance as many more were observed in the adjacent macadamia trees; the opposite was true for the *Nezara* species which were found on the trap crops and not in the macadamia trees. The ability to attract stinkbugs was not the only selection criteria for the best cover crop performers for phase one. Cultivation potential within an orchard system such as the ability to compete with weeds, drought resistance, long flowering periods and pod production (which attracts stinkbugs more than other stages of trap crop growth), and overall relatively easy cultivation potential were also important criteria to consider. Stinkbug damage to nut kernel was not assessed in phase one as the main aim of the first phase trials were to select the three best performing cover crops through a process of elimination.

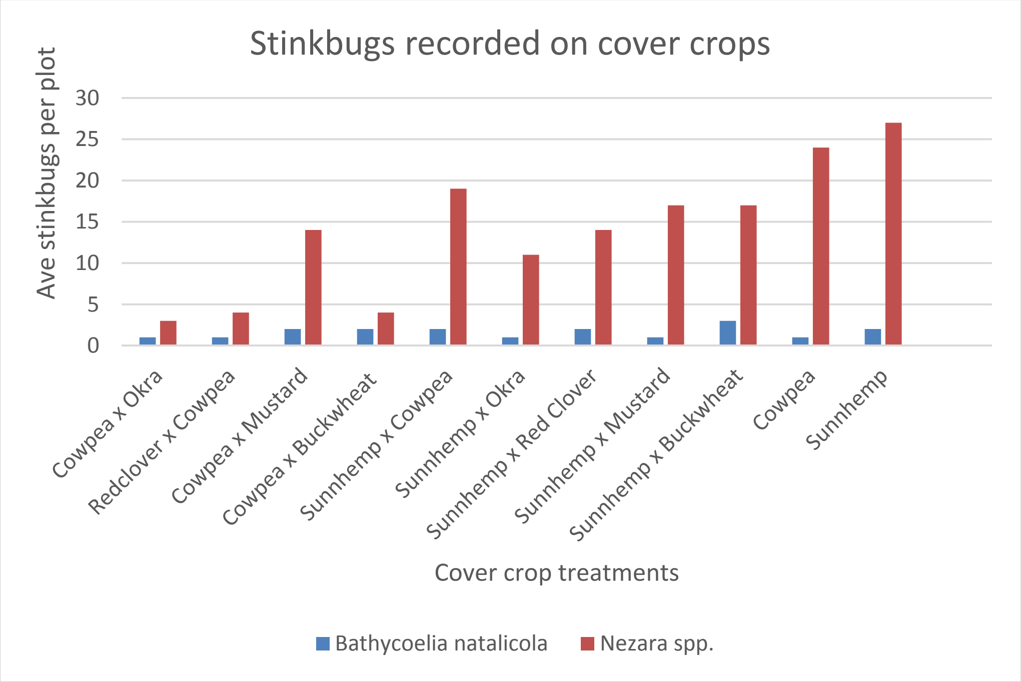


Figure 7. Phase one trials to assess trap crop potential of the cover crops showing the average total numbers of stinkbugs for all repetitions per trial plot for phase one.

1.4 Conclusion

The outcome of phase one (poor growth of cover crops in shade and competition with the main crop) resulted in the decision to relocate the cover crops into the orchard tree alleys for phase two. Based on the trap crop experiments, sunnhemp, mustard and cowpea were selected for phase two as these three had the highest potential as trap crops in a macadamia orchard system. All three crops are also renowned for their potential as "soil builders", which also made them suitable for the soil quality part of the study. For these reasons, only these three trap crops were cultivated in the second phase when the trials were repeated in 2011. The soil quality trials, however, also had to be modified after relocating the cover crops to the tree alleys; this involved the conversion of the cover crops to compost and then applying it as a mulch under the macadamia tree canopies.

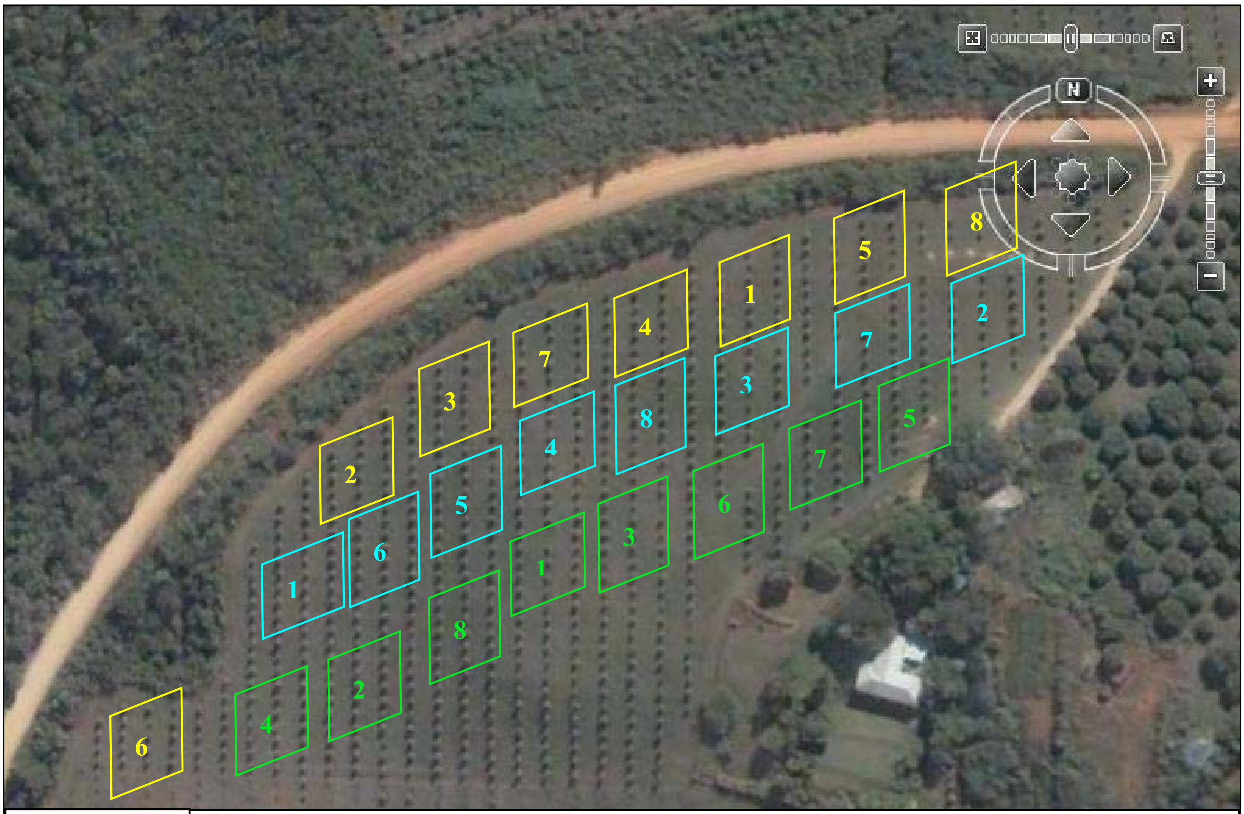
DATA CHAPTER TWO: PHASE TWO TRAP CROP FIELD TRIALS

2.1 Materials and Methods

This section reports the testing and further selection of suitable trap crops only; soil building studies is discussed under data chapter four, phase two. Only the three trap crops mentioned in phase one (mustard, sunnhemp and cowpea) were cultivated in the second phase of the trials. This was done in the form of a choice experiment (for the trap crop part of the study) with combinations of these three crops randomly located in similar trial plots as was done in phase one (Figure 8). This time these cover crops were cultivated between the tree rows (Figure 9) which solved the problem of shading and competition with the main crop. Nut kernel analyses for stinkbug damage were then conducted at the end of the growing season to assess the ability of the trap crops to shield macadamia nuts against *Nezara spp.* stinkbugs only, as it was clear from the onset that *Bathycoelia natalicola* could not be lured away from the main crop by any of the trap crops used in the trials. Phase two therefore involved an analysis of the nut kernel for stinkbug damage rather than monitoring stinkbug presence in the cover (trap) crops as was done in phase one.

2.1.2 Nut Kernel Analysis

Nut kernels were analysed for stinkbug damage (expressed as unsound kernel; USK) at the end of each harvesting season. USK resulting from stinkbug damage is clearly distinguishable on the kernel when the nuts are mature and dried to a kernel moisture content level of $\leq$ 4 %.



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1 = sunnhemp
2 = cowpea
3 = mustard
4 = cowpea x mustard
5 = cowpea x sunnhemp
6 =sunnhemp x mustard
7 = sunnhemp x cowpea x mustard
8 = control

Figure 8. Phase two trials with three cover crops cultivated in the orchard alleys

Figure 9. Mustard and cowpea treatment plot in orchard alley; phase two

2.2 Results and Discussion

The main purpose of the second phase was to test the potential of three trap crop treatments to reduce USK and to determine if cultivating within the tree orchard alley allowed proper growth of these plants. Nut kernel analyses at the end of the second phase revealed sunnhemp to have performed marginally (but not significantly) better than the other two cover crops, but significantly better than the control (one-way ANOVA, Tukey's test, $F_{[7,64]} = 3.272$, $p < 0.0049$) as a trap crop for stinkbugs (Figure 10). Although sunnhemp did not perform significantly better than the other two crops (cowpea and mustard), it had more favourable characteristics than the other two, such as longest flowering period and pod production, highest drought resistance and tallest crop. Furthermore, it did not create a breeding habitat for any of the stinkbug species, as no egg parcels were found on it during the surveys. Both the cowpea and the mustard mixture, however, displayed the potential to create breeding habitats for various stinkbug species. For this reason, two of the three trap crops were then rejected for the final round of trials. The mustard mixture (*Brassica hirta* and *Brassica juncea*) unfortunately also became a breeding host for the Green Vegetable Stinkbug (also known as the Southern Green Shieldbug, *Nezara viridula;* Figure 11).

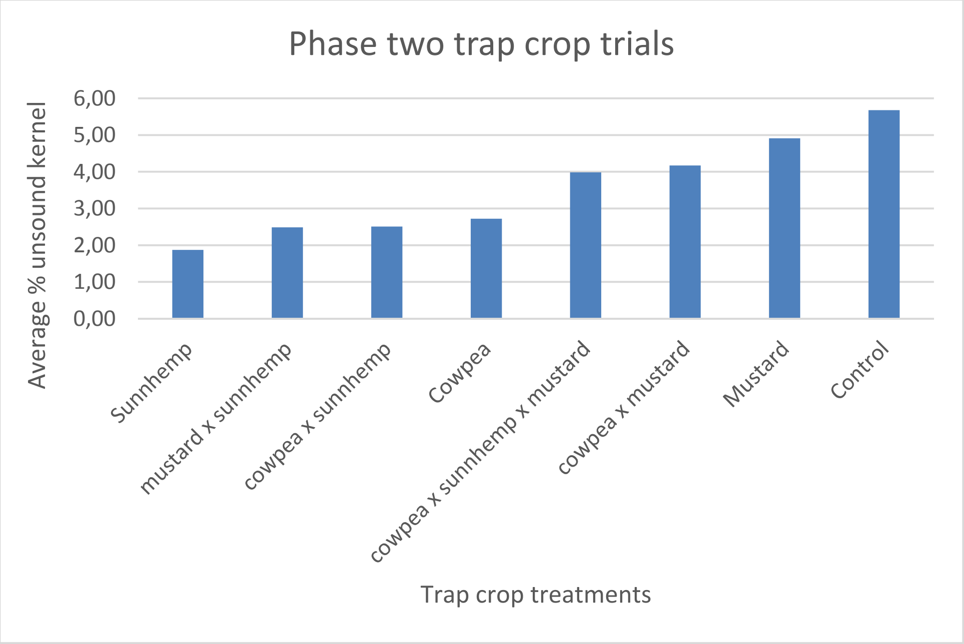

Figure 10. Average unsound kernel analysis for phase two trials for all repetitions

Figure 11. *Nezara viridula* nymphs (3rd instar) on mustard cover crop in the study area.

Similarly, the cowpea (*Vigna unguiculata*) showed signs of becoming a breeding host for the same species: studies have been documented where *N. viridula* used cowpea as breeding host (Lockwood and Story, 1986). Secondly, both these crops showed symptoms of susceptibility to fungal diseases, such as powdery mildew, which is common in the study area, because of the high humidity levels.

2.3 Conclusion

The outcome of phase two trials for trap crop experiments was that sunnhemp was selected for the final phase where the experiments were then duplicated on three different research sites (Figure 1), which were all organically managed macadamia orchards on commercial farms. Sunnhemp proved to be the most suitable trap crop for the study in all aspects as previously discussed. Sunnhemp did not, however, attract the two-spotted stinkbug (*Bathycoelia natalicola*) as mentioned before, but all the *Nezara* stinkbug species were strongly attracted to it. Although the two-spotted stinkbug poses a significant threat to macadamia nuts, especially in late summer and early autumn, sunnhemp could potentially at least cater for the *Nezara* species which are responsible for some or often most of the early stinkbug damage i.e. from August to December. The two-spotted stinkbug is the most dominant species when macadamia nuts are present in South Africa but is most prevalent in the late macadamia season (mid-January – June) and the other (maybe lesser important) stinkbugs (green vegetable, yellow edged and the small green stinkbugs) are more dominant in the early season (Nortje and Schoeman, 2016). Sunnhemp therefore has the potential to reduce pesticide spraying significantly, especially during the first half of the season when the *Nezara* species are more prevalent and cause the most damage to nuts.

DATA CHAPTER THREE: PHASE THREE TRAP CROP TRIALS

3.1 Materials and Methods

Sunnhemp was then selected for the third round of trials which were conducted (September 2012 – June 2013) on three macadamia farms (Figure 1 and Figures 12 - 14).

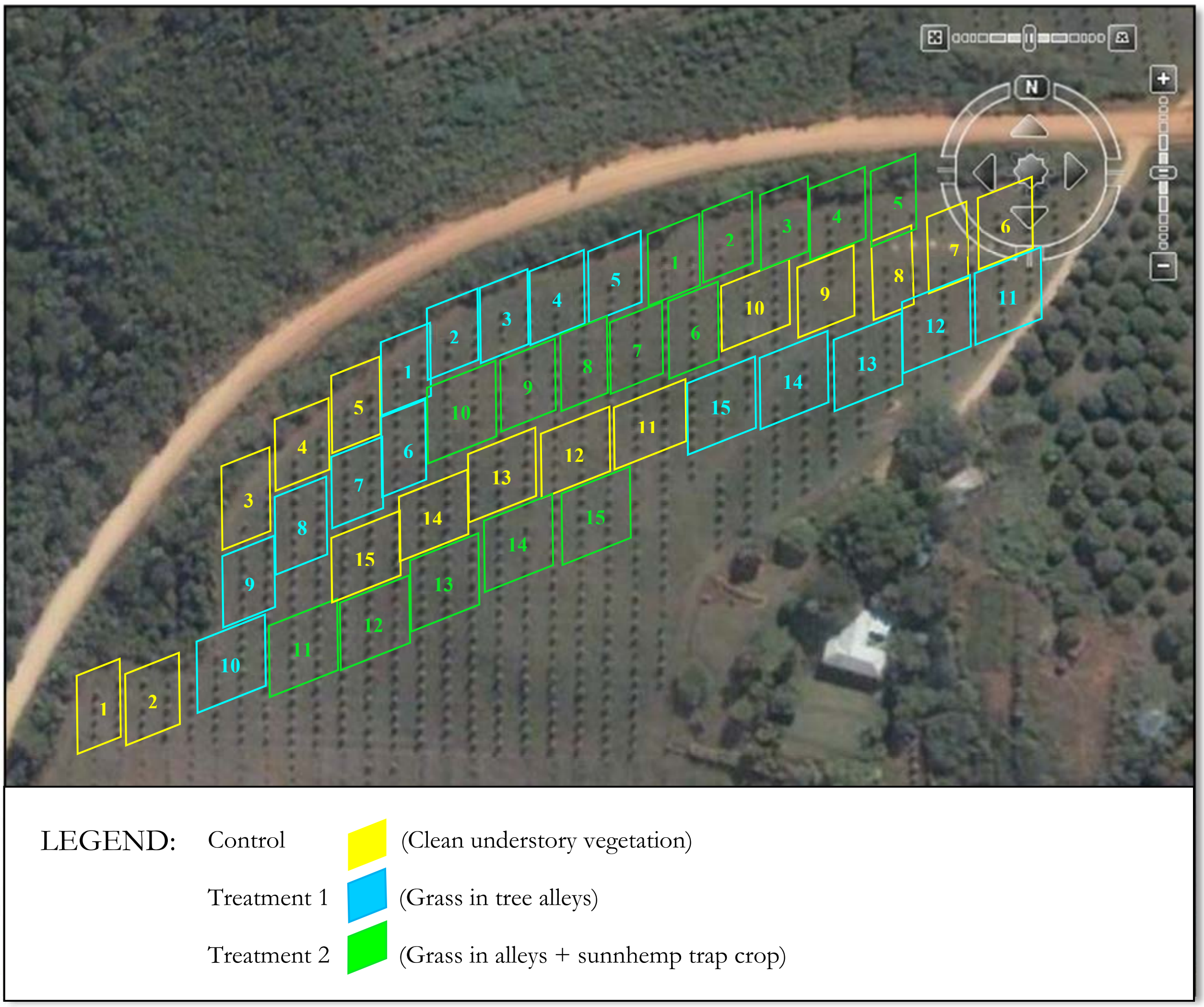

Figure 12. Two treatments and control replicated 15 times in research site 1 (Portion 28 of Welgevonden).

Final phase trials included two treatments and a control, namely enhanced orchard biodiversity with natural alley grass in the trial plots (Figure 15, treatment 1), trap crop (sunnhemp) in plots in addition to the alley grass of treatment 1 (Figure 16, treatment 2), and conventional orchard plots with clean understory vegetation (control). Nut kernel analyses of the treatments and control plots were conducted on nuts harvested from the trial plots of all three farms at the end of the growing season and compared statistically to assess the potential of sunnhemp to protect macadamia nuts against stinkbug pests. All treatments were replicated 15 times on all three research sites as follows; 5 plot replicates of each treatment located on the perimeter of the orchard (edge), 5 replicates midway to the centre and 5 replicates towards the centre of the orchard (Figures 12 – 14).

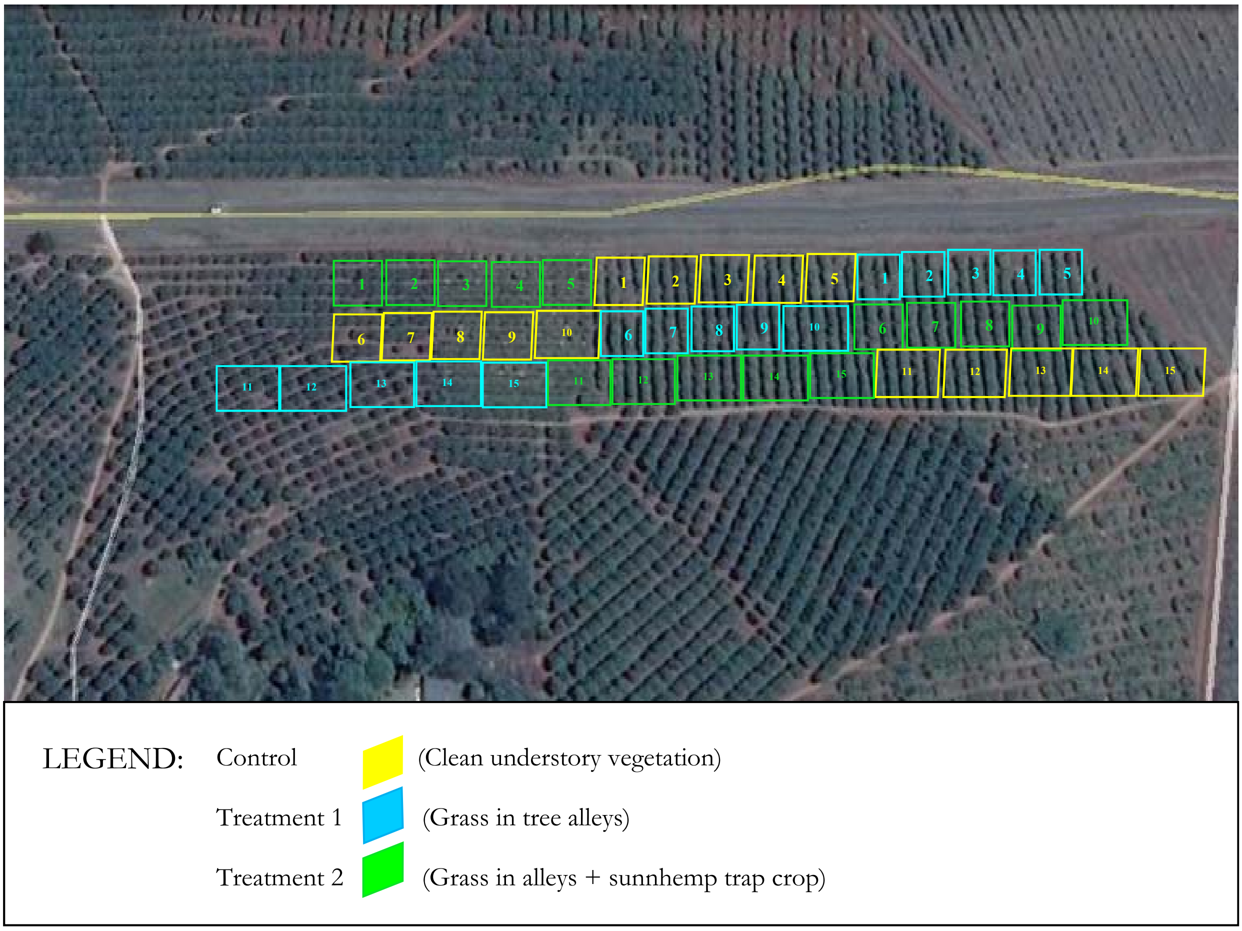

Figure 13. Two treatments and control replicated 15 times in research site 2 (Portion 3 of Piesanghoek)

All cover crops were tested for their ability to intercept dispersing stinkbug pests (Figure 17) from the alternate host plant (macadamia trees) in the study area. Although the fundamental principle here involved differential pest preference between plant species, the plants that functioned as trap crops and those to be protected (the diversity hypothesis cf. Altieri, 1989) was also tested, which postulates that insect pests are frequently less abundant in polycultures than in monocultures. Root (1973) termed this explanation for lower populations of insect pests in polycultures the *enemies' hypothesis,* where predators and parasitoids increase as natural controls of populations of insect pests. The latter author had a second explanation for the lower abundance of insect pests in polycultures, termed the *resource concentration hypothesis,* where insect pests, particularly with a narrow host range, have greater difficulty in locating and remaining upon host plants in small, dispersed patches as compared to large, dense, pure stands. Vandermeer (1981) provided a third reason, also known as the *trap crop hypothesis,* where herbivores are attracted to associated (trap) plants and that trap crops act preferentially to attract generalist herbivores in such a way that the plant to be protected is not as likely to be directly attacked.

The first treatment included only an increase in habitat heterogeneity by enhancing orchard floor diversity (Figure 15) to compare the influence of a diverse environment to a simplified one as was found in the control. The second treatment combined an enhancement of orchard floor diversity with the trap crop (Figure 16).

Figure 14. Two treatments and control replicated 15 times in research site 3 (Remaining portion of Vlakfontein).

Figure 15. Orchard alleys with increased habitat heterogeneity by enhancing natural vegetation diversity (and natural predator habitat) in the trial plots.

Figure 16. Sunnhemp with enhanced alley vegetation as a treatment

Figure 17. Green stinkbugs (*Nezara viridula*) on sunnhemp (*Crotolaria juncea*) trap crop

3.2 Statistical Methods

For statistical analyses, normality was tested using a Shapiro-Wilks test (Zar, 1997) of the dependent variable: unsound kernel (%). Categorical parameters included site: Piesanghoek (Site 1), Vlakfontein (Site 2) and Welgevonden (Site 3); location of sampled kernel: Centre, Midway, Edge (N = 5 replicates per site, location and treatment; and treatment: none (Control), natural vegetation (Diversity) and natural vegetation with additionally planted trap crops (Diversity + Trap Crop). The assumption of over-dispersion was verified for each model ensuring that the residual deviance is smaller than the degrees of freedom (d.f.). Generalized Linear Models (GLZ) were employed when the distribution of the errors did not meet the assumption of normality. Assumption tests and ANOVA's were undertaken in R (v. 3.3.1, R Development Core Team 2016).

Based on assumption tests specified chi-squared tests were performed. In some instances, homogeneous groups were assigned by using overlap in 95% CLs (triangular notches from the median) from box plots (Crawley, 2007) and interpreted in addition to post-hoc test results. The bottom and top of the box are the 25th and 75th percentiles (the lower and upper quartiles, respectively), and the band near the middle of the box is the

50th percentile (the median). Whiskers represent the data range (minimum and maximum value, excluding outliers). Outliers on the high or low end of the data ranges were identified as values 3/2 times higher or lower than the upper or lower quartiles respectively.

3.3 Results

3.3.1 Introduction

The main question which needed to be answered in this part of the study was whether cover crops combined with an increase in habitat heterogeneity could be utilized in sub-tropical fruit orchards as a more sustainable alternative to inorganic pesticides to protect macadamia crops against stinkbug pests by reducing the impact of the pest insects significantly without compromising crop quality.

3.3.2 Trap Crop Trials

The complete unsound kernel percentage dataset data did not meet the assumption of normality (Shapiro-Wilk normality test, W = 0.96; $p < 0.001$) and is plotted in Figure 18; the non-parametric ANOVA results are summarized in Table 2. The results showed that the interaction effect as well as the main effects of site and treatment significantly affected the unsound kernel percentage. I therefore interpret the results separately per Site. The interaction effect between treatment and location at each site are again considered, and if significant, not grouped.

Table 2. Summary results from a generalized linear model testing the main and interaction effects of site, treatment and location in the orchard on the unsound kernel percentage (Gaussian distribution of errors, log link function). Interaction effects are presented with × and the degrees of freedom (d.f.), chi–square ($\chi 2$) statistics and corresponding P–values are shown.

	χ^2	**d.f.**	***P*-value**
Site	32.61	2	<0.0001
Treatment	110.99	2	< 0.0001
Location	5.56	2	0.0620
Site x Treatment	25.58	4	<0.0001
Site x Location	24.38	4	<0.0001
Treatment x Location	16.46	4	0.0025
Site x Treatment x Location	27.80	8	0.0005

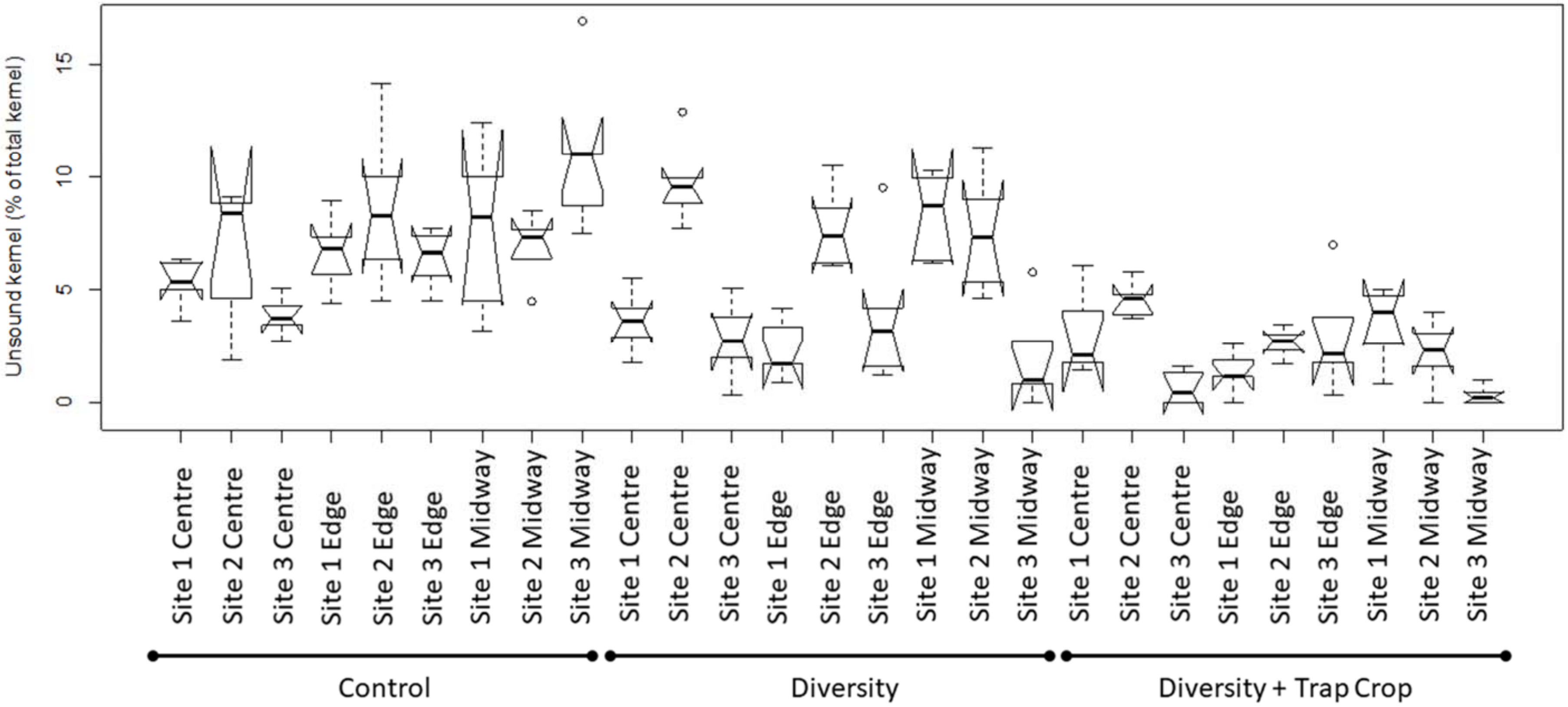

Figure 18 Box-plot showing medians, outliers and data ranges (box = 50th quartiles, whiskers = min-max) with triangular notches from the median for the effects of treatments: Control, Diversity and Diversity + Trap Crop; Site and location (Centre, Edge, Midway) on the unsound kernel percentage.

At Site 1 (Piesanghoek), the data distribution was normal (Shapiro-Wilk normality test, W = 0.96; p = 0.079). The results from the ANOVA are summarized in Table 3 showing a significant interaction effect of the treatment and location in the orchard on the unsound kernel percentage. The effects of the ANOVA and treatment per location is summarized in Table 4 and 5 respectively. There were no significant treatment differences in the centre of the orchard at Piesanghoek. At the orchard edge and midway through the orchard the difference in treatment effects were significant (Table 4). A diverse orchard without trap crop midway through the orchard had a significantly higher unsound kernel percentage in comparison to the same location with a trap crop (Table 5, Figure 19A). At the edge of the orchard the control performed significantly worse (i.e. higher unsound kernel percentage) than the treatments where there were diversity and trap crops. The latter two treatments did not show significantly different results. There was no significant location effect when compared within the Control group (ANOVA: $F_{(2, 12)} = 1.11$, *P*-value = 0.36). Within the Diversity orchard treatment group, a significantly higher unsound kernel percentage was found midway through the orchard (ANOVA: $F_{(2, 12)} = 19.43$, *P*-value < 0.001). There were no significant location effects when compared within the Diversity + Trap Crop group (ANOVA: $F_{(2, 12)} = 2.40$, *P*-value = 0.13). The results are plotted in Figure 19A.

At Site 2 (Vlakfontein), the data distribution was normal (Shapiro-Wilk normality test, W = 0.98; p = 0.667). The results from the analyses showed no significant interaction effect between treatment and location in the orchard (ANOVA: $F_{(4, 36)} = 1.46$, *P*-value = 0.23). The main effects test showed only a significant treatment effect (Table 3) and the outcomes of the treatments are summarized in Table 4 and 5. There was a significantly lower unsound kernel percentage at the Diversity + Trap Crop treatment than in the Control and Diversity treatments (Pairwise t-test: p < 0.0001 in both cases). The only significant location (higher unsound kernel percentage) effect was found in the Diversity + Trap Crop treatment group, at the Centre of the orchard (Figure 19B, ANOVA: $F_{(2, 12)} = 6.92$, *P*-value = 0.01).

At Site 3 (Welgevonden), the data distribution was not normal (Shapiro-Wilk normality test, W = 0.87; p < 0.001). The results from the generalized model as summarized in Table 6 show a significant interaction effect of the treatment and location in the orchard on the unsound kernel percentage. The effects of the ANOVA and treatment per location is summarized in Table 4 and 5 respectively. There were no significant treatment differences in the edge of the orchard at Welgevonden. At the orchard centre and midway through the orchard the treatment effects were significant (Table 4). A diverse orchard with trap crop resulted in a significantly lower unsound kernel percentage in comparison to a diverse orchard without trap crop and the control. The control group performed significantly worse than both treatments midway through the orchard (Figure C). There was a significant location effect when compared within the control group (ANOVA: F(2, 12)= 12.71, P-value = 0.001) with a significantly higher unsound kernel percentage midway through the orchard. Within the Diversity and Diversity + Trap Crop orchard treatment groups, no significant difference were found (ANOVA: F(2, 12)= 0.68, *P-value* = 0.52 and GLZ: $\chi 2 = 3.10$, d.f. = 2, *P*-value = 0.21).

Table 3 ANOVA results at Sites 1 and 2 showing the effect of treatment, location and the interaction on unsound kernel percentage.

	Sum of squares	**d.f.**	***F*-value**	***P*-value**
Site 1: Piesanghoek				
Treatment	115.15	2	15.23	< 0.0001
Location	76.94	2	10.17	0.0003
Treatment x Location	46.83	4	3.10	0.027
Residuals	136.09	36		
Site 2: Vlakfontein				
Treatment	231.13	2	22.67	< 0.0001
Location	15.65	2	1.54	0.23
Residuals	203.95	40		

Table 4 ANOVA outcomes per site and location for the treatment effect on unsound kernel percentage.

	Sum of squares	**d.f.**	***F*-value**	***P*-value**
Site 1: Piesanghoek				
Location: Centre				
Treatment	13.561	2	2.88	0.09539
Residuals	28.288	12		
Location: Edge				
Treatment	78.444	2	20.87	0.00012
Residuals	22.552	12		
Location: Midway				
Treatment	69.969	2	4.92	0.02745
Residuals	85.248	12		
Site 2: Vlakfontein				
Treatment (grouped location)	231.13	2	22.10	< 0.0001
Residuals	319.60	42		
Site 3: Welgevonden				
Location: Centre				
Treatment	26.22	2	8.40	0.0052
Residuals	18.73	12		
Location: Edge				
Treatment	29.76	2	2.31	0.14
Residuals	77.49	12		
Location: Midway				
Treatment	329.67	2	36.59	< 0.0001
Residuals	74.39	12		

Table 5 Summary of the treatment results on the unsound kernel percentage with the significance level within each group.

Location	Treatment	Mean	std. dev.	s.e.	Significance level (within group)
Site 1: Piesanghoek					
Centre	Control	5.32	1.12	0.5	a
	Diversity + Trap Crop	3.1	1.97	0.88	a
	Diversity	3.6	1.39	0.62	a
Midway	Control	7.66	3.81	1.7	ab
	Diversity + Trap Crop	3.42	1.73	0.77	a
	Diversity	8.28	1.94	0.87	b
Edge	Control	6.62	1.69	0.76	a
	Diversity + Trap Crop	1.34	0.98	0.44	b
	Diversity	2.36	1.35	0.6	b
Site 2: Vlakfontein					
Centre	Control	6.86	1.52	1.7	ab
	Diversity + Trap Crop	2.2	1.52	0.77	a
	Diversity	7.52	2.72	0.87	b
Midway	Control	8.66	3.67	0.76	a
	Diversity + Trap Crop	2.62	0.65	0.44	b
	Diversity	7.76	1.84	0.6	a
Edge	Control	6.56	3.18	0.5	a
	Diversity + Trap Crop	4.56	0.83	0.88	b
	Diversity	9.78	1.94	0.62	a
Site 3: Welgevonden					
Centre	Control	11.02	3.62	1.62	a
	Diversity + Trap Crop	0.32	0.41	0.19	b
	Diversity	2.06	2.31	1.03	a
Midway	Control	6.36	1.32	0.59	a
	Diversity + Trap Crop	3.02	2.55	1.14	b
	Diversity	3.94	3.34	1.49	b
Edge	Control	3.84	0.91	0.41	a
	Diversity + Trap Crop	0.66	0.75	0.33	a
	Diversity	2.78	1.82	0.81	a

Table 6 Summary of the generalized linear model results (normal distribution of errors and a log link function) for the unsound kernel percentage. The main- and interaction-effect of treatment and location are given. The degrees of freedom (d.f.), chi-square ($\chi 2$) statistic and p-value (*P*) is presented and × indicates an interaction effect.

Effect	X^2	d.f.	*P*-value
Treatment	55.58	2	< 0.0001
Location	8.67	2	0.013
Treatment x location	25.79	4	< 0.0001

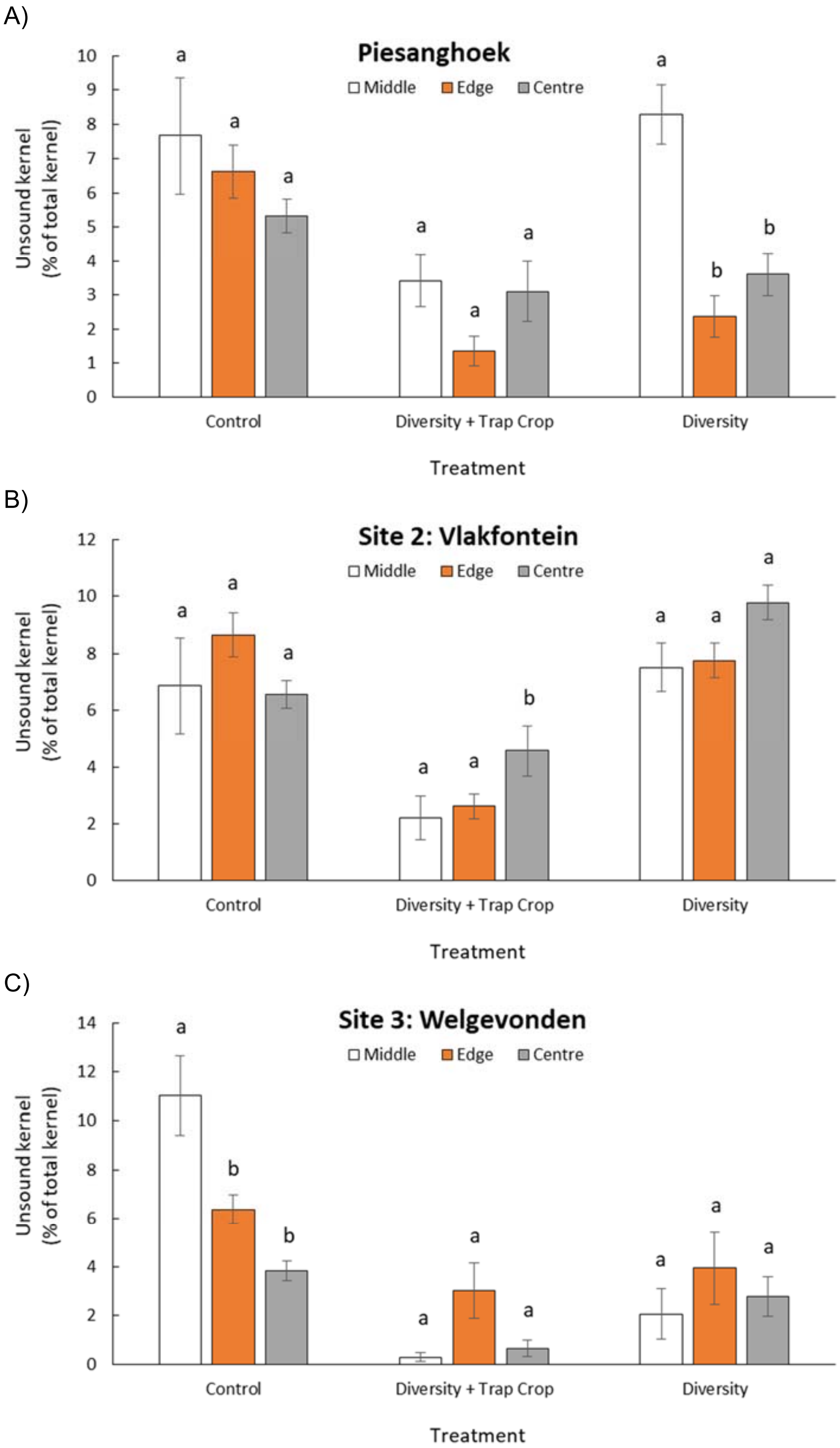

Figure 19 Treatment summary and significance levels of the effects of location within the orchard in each treatment grouping on the unsound kernel percentage for each site (mean ± std error).

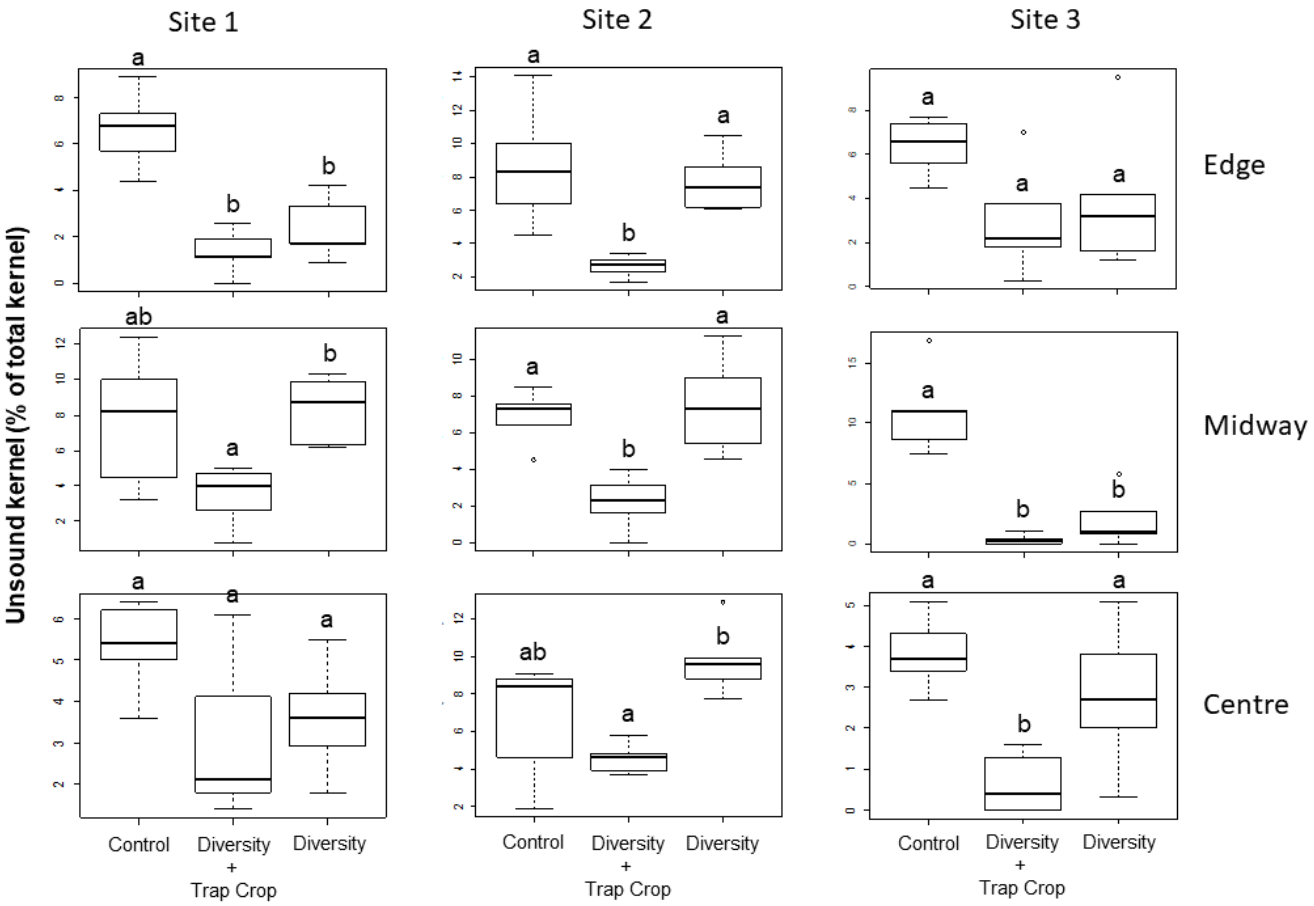

Figure 20 Box-plots of the treatment effects across site and location. Significance levels are indicated by letters.

3.4 Discussion

Stink bugs are believed to occur in a clustered distribution (or hot-spots) in homogenous orchards. However, in this study there was no consistency in damage levels at specific locations, i.e. damage associated with the centre, edge or midway through the orchard, and, except for three cases the location effect was not significant (Figure 20). It would therefore be wrong to say that damage was mostly located in the centre of the orchards.

The results from this study shows a significant effect of trap crops combined with increased orchard diversity in reducing unsound kernel percentages, especially at sites 2 and 3 (Figures 21 and 22). The results suggest that trap crops combined with an increase in orchard diversity could be utilized in sub-tropical fruit orchards as a more sustainable alternative to inorganic pesticides against the stinkbug complex in macadamia.

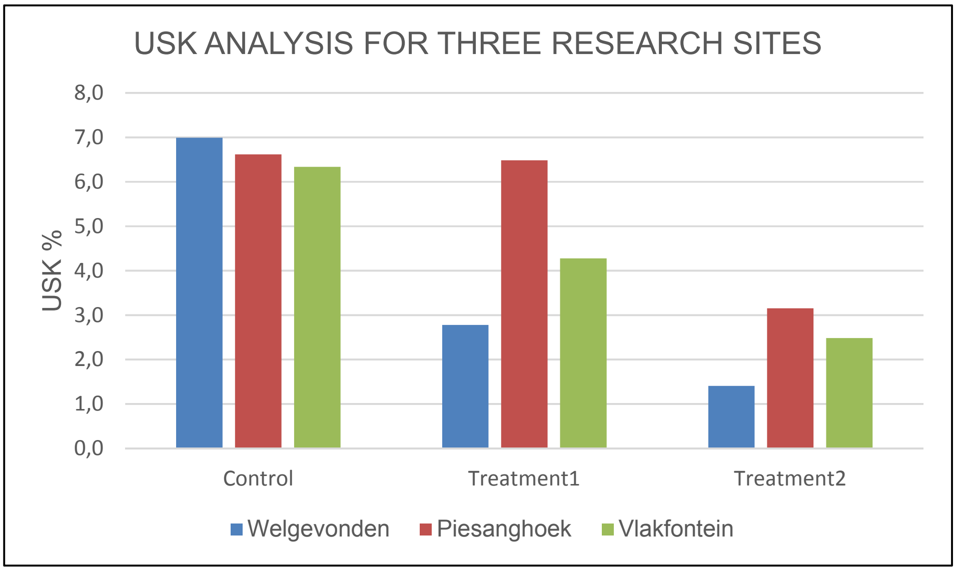

Figure 21. Control and treatment plots compared for the three sites

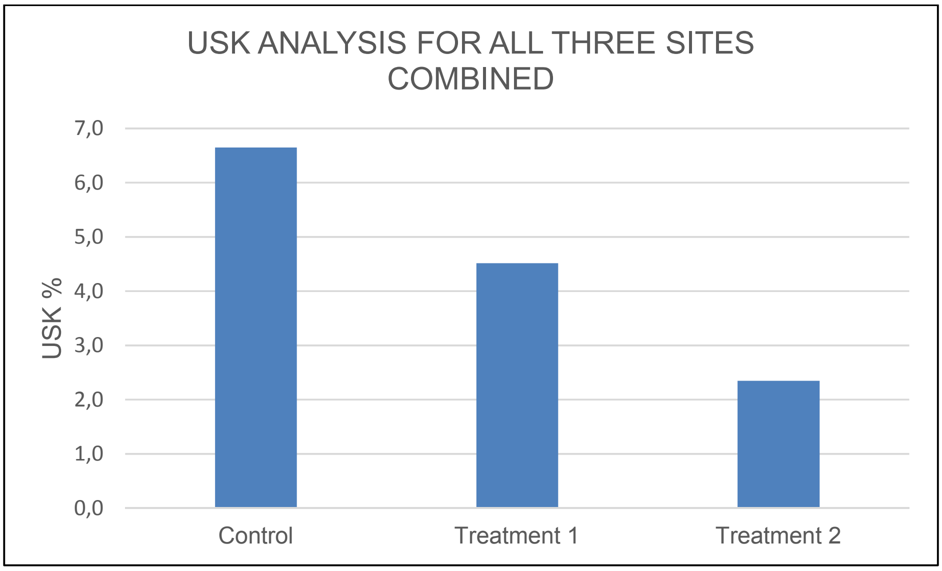

Figure 22. Controls and treatments of all sites compared collectively

DATA CHAPTER FOUR: PHASE TWO SOIL BUILDING FIELD TRIALS

4.1 Materials and Methods

4.1.2 Field Trial Experiments

This section deals with soil building trials conducted with the same cover crops (sunnhemp, cowpea and mustard) tested for their trap cropping abilities in the first section of Data Chapter Two, phase two. Solving one problem, however, created another one as the main potential advantage of the cover crops (as soil builders) was virtually nullified when they were removed from the target root zone area from under the tree canopy to inside the orchard alleys in phase two (Figure 16). Another strategy had to be implemented to compensate for this, and it was decided to compost the cover crop biomass first before returning it to the target root zone areas (under the tree canopy) as a mulch. The cover crops in the trial plots were consequently mowed at maturity (and after the macadamia crop had been harvested) and composted with other available compost materials on site, which included macadamia nut husks, wood chips, grass and sheep manure.

This compost product could however not be produced fast enough and in adequate quantities for the research project trials and a commercially produced compost (Table 7) was used in addition. Two compost (mulch) treatments were applied in the second phase of the trials (Figure 23); 0.5 m^3 and 1 m^3 of compost per tree under the canopy of the trees respectively and a control where no compost was applied. This amounted to 0.5 m^3 of compost per 16 square metres of soil for treatment one and 1 m^3 of compost per 16 square metres of soil for treatment two. These quantities were based on recommendations by Jenkins (2004) for the use of compost in macadamia orchards in Australia.

These two treatments were conducted with trees which were growing in what appeared to be healthy soils, and then repeated with trees in the same orchard where the topsoil had been degraded (totally removed) by agricultural operations (Figure 24). This orchard used in phase two for this purpose was a different orchard adjacent to the one used in phase one. It was decided to use this orchard rather as it provided an opportunity to include and measure the effect of compost not only on undisturbed soils, but degraded soils of the same type adjacent to the undisturbed experimental plots. The topsoil had been completely removed in the latter case (Figure 25). All compost treatments were replicated seven times and repeated twice over a period of 16 months before soil samples were collected and analysed. Soil samples were collected from all treatment and control plots and analysed for several biological, physical and chemical properties considered to be important indicators of soil quality as proposed by Steyn et al., (2014) to compare changes in the soil for all compost treatments (Appendix D).

Table 7. Comparison of chemical analysis of compost used in project trials

Sample	N %	P %	K %	Ca %	Mg %	Zn mg/kg	Cu mg/kg	Mn mg/kg	Fe mg/kg	B mg/kg	N:K
Commercial compost	1.21	0.564	1.24	1.25	0.714	246	63	422	15750	209.5	0.6
Cover crop compost	1.3	0.2	2.14	0.58	0.387	62	89	1064	33307	369.1	0.6

Figure 23. Compost applied as a surface mulch in the undisturbed soil trial plots; phase two.

Figure 24. Compost applied as a surface mulch in the degraded soil trial plots; phase two.

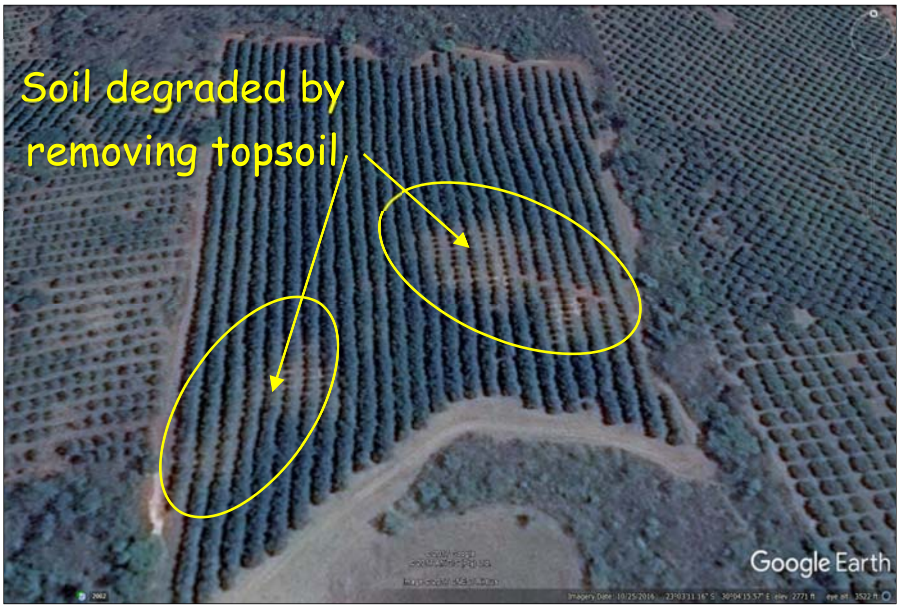

Figure 25. Trials repeated in degraded soil where topsoil had been removed to modify slope of the orchard prior to cultivation

4.1.3 Soil Quality Indicator Analyses

Indicators which reflect soil quality were chosen to measure changes in the soil of the study area which were treated with compost applications. Management goals as defined by the macadamia producing industry in South Africa include measures for more sustainable cultivation practices, which are those based on ecological principles that may enhance the ecological processes of nutrient cycling and release, enough to reduce the dependency on and use of synthetic chemical fertilizers. The main goal of this part of the study was to investigate the potential of cover crops to enhance growing conditions for macadamia trees, with the focus on optimum soil conditions for root growth and development as well as nutrient availability and water retention. Soil samples (excluding remains of compost mulch) were collected from the centre of each trial plot of the compost treatments six months after the second treatment (compost application) and analysed for the following selected soil quality or health assessment indicators as proposed by Steyn et al., (2014):

Chemical Properties

The following indicators were measured by making use of the services of an accredited soil laboratory (Bemlab: SANAS accreditation no: T0475; see Appendix B for soil analyses values) where standard soil analysis procedures were used to measure the following aspects of the soil:

i) Exchangeable macronutrients
ii) Micronutrient concentrations
iii) pH
iv) Electrical conductivity
v) Cation exchange capacity and cation ratios

Physical Properties (see Appendix B for soil analysis values)

i) Aggregate stability: The wet sieving method as proposed by the basic protocol from the soil health testing laboratory (Gugino et al., 2009) was used with the aid of a rain simulator sprinkler developed by the University of Cornell soil health division to determine the aggregate stability.

ii) Available water capacity: Water was extracted from soil samples under pressure to determine the available water capacity as described by the protocol developed by Gugino et al. ,(2009)

iii) Surface and subsurface hardness (measurement of soil strength): Field penetration resistance was measured using a field penetrometer, an instrument that measures soil resistance to penetration; applying the basic protocol developed by Gugino et al., (2009).

iv) Bulk density: The weight of the soil was measured underneath the compost layer by driving a steel ring of known volume, 6cm deep into the soil and calculating the core's dry weight by weighing and oven drying at 105°C for 24 hours. Tests were conducted by Bemlab (SANAS accreditation no: T0475).

Biological Properties (see Appendix B for soil analyses values)

i) Earthworm abundance: assessed by making use of the formalin expulsion technique (Satchell, 1971). Square frames of 0.25 m^2 were used for this purpose to record earthworm numbers in trial plots.

ii) Organic matter content: The percentage organic matter was determined by loss on ignition, based on the change in weight after the soil was exposed to approximately 510°C in a furnace following the basic protocol as proposed by Gugino et al., (2004).

iii) Active carbon content: soil samples were mixed with potassium permanganate and as it oxidized, the active carbon changed colour, which could be observed visually, but was measured with a spectrophotometer following the basic protocol as proposed by Gugino et al., (2004).

iv) Potentially mineralizable nitrogen (PMN): Here soil samples were incubated for 7 days and the amount of ammonium produced in that period reflected the capacity for nitrogen mineralization following the basic protocol proposed by Gugino et al., (2009).

v) Nematode populations: these were analysed with the aid of the weighted nematode faunal analysis (Ferris and Bongers, 2009) which measures structure and enrichment of nematode populations.

vi) Springtail (Collembola) community profiling: samples of leaf litter and topsoil were collected and processed with Berlese funnels to extract the springtails (Sutherland, 1996).

4.2 Statistical Methods

4.2.1 Introduction

For statistical analysis, all dependant variables (soil quality indicators) that were analysed for trial plots e.g. the soil physical (7), chemical (25) biological (10), and nematodes (38 species) were first subjected to a Linear Discriminant Analyses (LDA) using the Correlation Matrix (Rencher, 2002). All these indicators were then individually analysed in R (v. 3.4.3, R Foundation for Statistical Computing, 2008, Vienna, Austria; Packages 'stats', 'nnet', 'MASS', 'Performance Analytics' and 'car').

4.2.2 Linear Discriminant Analyses (LDA)

LDA was performed using XLSTAT for Microsoft Office 2013 with a statistical add-on module to Excel. LDA allowed for the study of the differences between all plots with respect to all the above variables simultaneously, determining whether meaningful changes occurred between the plots after treatment and to identify the discriminating power of each variable which would explain some of the unexpected changes with respect to some variables. The forward stepwise method of selection was chosen here with the probability for variables to enter as $p=0.05$ and to be removed as $p=0.10$ with the assumptions that the within-class covariance matrices are equal and to take the prior probabilities into account.

4.2.3 R Analyses

From the R analyses, the null-hypotheses were first rejected on an alpha level of 5% ($p = 0.05$) in all cases. The data distribution was verified using the Shapiro-Wilk test. When the assumption of normality of the dependent variable was verified, a linear model (LM) was used. When the assumption of normality of the dependent variable was violated (p-value < 0.05), a generalized linear model (GLZ) was used. Statistical results are reported in text or tabled in all cases. Results for the GLZ are the log likelihood chi-square statistic (LR χ^2) with degrees of freedom (d.f.) in brackets and p-value of the model. Results for the LM are given as the sum of squares (SS), d.f., F-value and p-value of the model. The interaction effects between soil type and treatment were always analyzed first and tabled, and if non-significant, main effect outcomes were reported. Continuous data were analyzed using a Gaussian distribution of errors and identity link function and count data was analyzed using a quasi-Poisson distribution of errors and log link function. Residual deviance was checked against d.f. to solve for any over-dispersion issues through data transformation (Crawley, 2007). Bartlett's test of homogeneity of variance was employed to verify that the variances were equal. Appropriate post-hoc tests were employed (LM: pairwise comparison using t-tests with pooled standard deviation; GLZ: multiple comparison test after Kruskal-Wallis). If the post-hoc test was not able to identify levels of significance described by the model estimates, overlap in 95% CLs was used to test for statistically significant homogeneity among compost treatments.

For two-way comparisons, data distribution was verified with the Shapiro-Wilk test and an F-test was used to compare two variances. A t-test was used or alternatively a Welch Two Sample t-test when the variances were not equal, or a Mann-Whitney U-test when the data did not meet the assumption of normality.

The data from the nematode analyses were ordinal and analysed using a chi-squared test following the contingency table. The outcomes (dependent variable) were categorized into three levels. The predominant population structure obtained per replicate were considered in determining the treatment combination outcome. There were two predictor variables: 1) soil type with two levels, healthy soil *vs.* degraded soil and 2) treatment with three levels: half compost, full compost and control.

4.3 Results

4.3.1 Introduction

The main question which needed to be answered in this part of the study was whether cover crops could potentially be utilized in sub-tropical fruit orchards to enhance soil quality with the aim of improving nutrient cycling and release so that inorganic agrochemical inputs could be reduced without compromising crop yield. The rationale here was that high quality soils are synonymous with rich growing conditions for plants which may then be less dependent on agrochemicals. The outcome of phase one clearly showed that cover crops should not be cultivated within the root zones of the main crop. The decision to compost the cover crops and then apply it as a mulch in the target soil root zone of the macadamia trees (under the tree canopies) in phase two of the trials may therefore have contributed significantly to soil quality (Ding et al., 2006; Clark, 2007; Steenwerth and Belina, 2008a). Soil analyses (see Appendix B for soil analyses values) from the trial plots located in the tree alleys were therefore compared to determine what impact the compost treatments had on soils of the healthy as well as the degraded soil plots.

4.3.2 Results: Linear Discriminant Analyses

The first analyses (LDA) is portrayed in Figure 26 and represents the observations on the factor axes. It confirms that the soil samples of the trial plots were very well discriminated by the Factor 1 axis extracted from the explanatory variables. It also shows the positive and negative drivers discriminating for each factor. Factor 1 is accordingly mainly responsible for discriminating between the healthy and degraded soils and the positively correlated variables here are exchangeable Mg and Mg content and the negatively correlated variables are bulk density (the only soil physical variable), the Ca: Mg ratio, exchangeable Ca and exchangeable K. Factor 2 mainly distinguishes between compost levels and the correlates for discrimination in this case are the positively correlated variables exchangeable Na, Fe and Na content. The factor 1 and 2 loading correlations by variable is displayed in Appendix C: Figure 1 and Table 1.

All these factors changed (improved) with compost treatments (Figure 26). The only negatively correlated variable was Cu (all from the soil chemical variables). As illustrated in Figure 26, Cu decreased when compost increased, which can be attributed to a Cu negative period. Na conversely increased with increasing compost application because of the dissolved minerals in the manure, which was a major ingredient in the compost, as more compost was added. Mg content was lower in the healthy soil than in the degraded soils but improved with compost additions. The soil biological variables and nematode species played a minor role. The overall discrimination was with a 91.67% accuracy. The confusion matrix in Appendix C, Table 2 shows a perfect discrimination of all treatments using the selected variables.

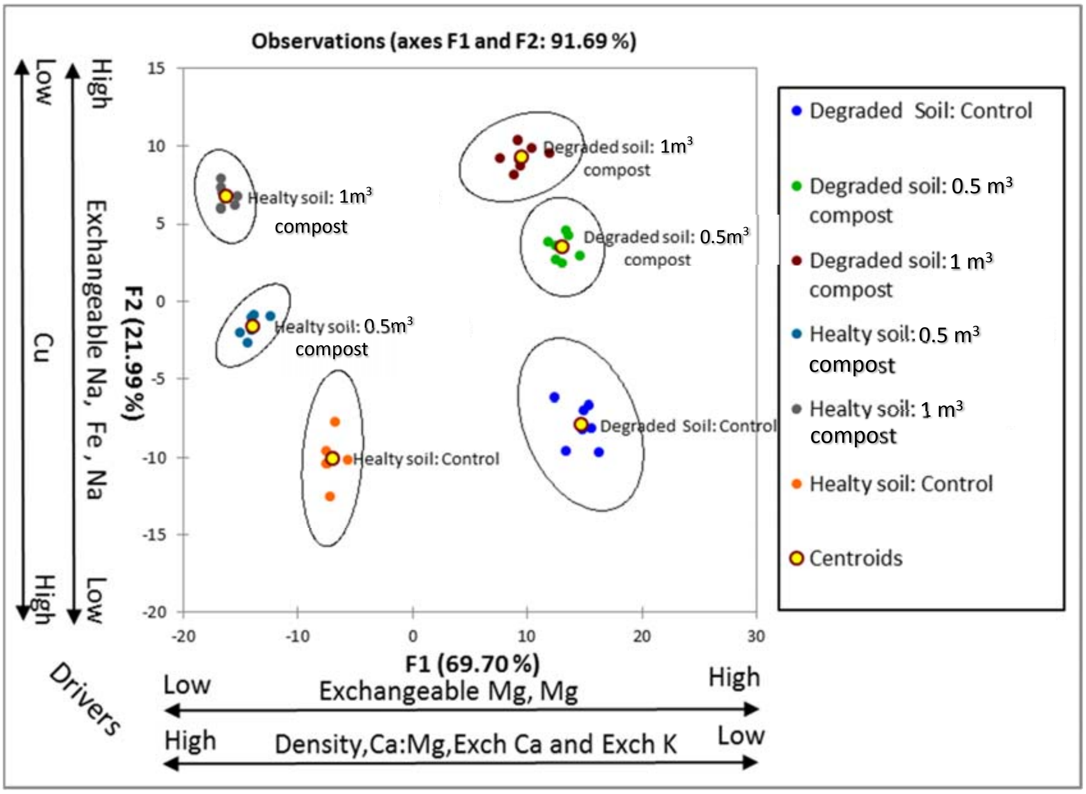

Figure 26: The important drivers associated with each factor that causes the discrimination between soils and between treatments.

As illustrated in Figure 26 all the trial plots were significantly different from each other ($p < 0.0001$; Table 8). Both treatments effected significant changes in the healthy as well as the degraded soils. Figure 26 shows how the plots in the healthy (or rather undisturbed) soil separated clearly from the degraded (topsoil) plots and how both treatments with compost effected a significant shift (change) in the soil (according to the selected soil quality indicators) in both the degraded as well as the healthy soil.

Table 8. Wilk's Lambda test (Rao's approximation)

Lambda	0.000
F (Observed value)	20.536
F (Critical value)	1.408
DF1	95
DF2	92
p-value	< 0.0001
α	0.05

4.3.3 Results: R Analyses

An analysis of all variables (soil quality indicators) individually, revealed how the additions of compost changed some of the dependant variables like pH and the status of some nutrient elements significantly. The main question to be answered now was whether these changes reflected an improvement in soil quality, particularly from a macadamia cultivation point of view. The health statuses of all trial plots were determined after the treatments by using the soil quality indicators as proposed by Steyn et al., (2014) as criteria. For the study however, ideal soil conditions for the cultivation of macadamia trees (Kuperus and Abercrombie, 2003 adapted by Nortjé, 2017) were used as a benchmark to assess the changes in the trial plots (Appendix A). This standard may not be perfect as a representation of ideal soil quality under all conditions and for all cultivation purposes but was nonetheless chosen as the most appropriate one for the study. Most of the soil quality indicators that were analysed displayed an improvement in soil quality from this point of view.

4.3.3.1 Soil Type Differences

An analysis of the commercial compost applied, is shown in Table 9 and the characteristics of the two different soil types where compost trials were conducted on are summarized in Table 9.

Table 9. Chemical analysis of compost applied onto two different soil types at two different rates: 0.5 m^3 and 1 m^3 per tree drip area (16 m^2) for comparison to an untreated control.

Chemical parameter	Value
N (%)	1.21
P (%)	0.56
K (%)	1.24
Ca (%)	1.25
Mg (%)	0.71
Zn (mg/kg)	246
Cu (mg/kg)	63
Mn (mg/kg)	422
Fe (mg/kg)	15750
B (mg/kg)	209.5
N:K ratio	0.6

Table 10. Summary table for measured parameters in healthy soil and degraded soil where no compost was applied. Means ± standard errors are given; significant differences are indicated with an asterisk (*).

Parameter	Healthy soil	Degraded soil
Physical soil properties		
Available water capacity (g/g)	97.84 ± 1.47	97.39 ± 2.27*
Soil aggregate stability (%)	92.71 ± 1.19	86.96 ± 1.75*
Soil penetrability (psi)	9.43 ± 2.52	3.36 ± 0.21*
Bulk density (g/cm^3)	1.02 ± 0.01	0.92 ± 0.01*
Clay content (%)	43.51 ± 0.73	40.95 ± 2.01
Sand content (%)	42.63 ± 0.73	36.19 ± 4.28
Silt content (%)	13.86 ± 0.59	22.86 ± 2.43*
Chemical soil properties		
Exchangeable Ca (%)	68.15 ± 2.06	45.50 ± 1.39*
Exchangeable K (%)	10.19 ± 0.72	1.11 ± 0.25*
Exchangeable Mg (%)	19.54 ± 1.71	51.77 ± 1.63*
Exchangeable Na (%)	2.12 ± 0.55	1.63 ± 0.19
P (mg/kg)	28.49 ± 3.54	1.38 ± 0.38*
K (mg/kg)	497.86 ± 32.98	78.46 ± 14.31*
Ca (mg/kg)	1754.27 ± 173.32	1897.33 ± 191.83
Mg (mg/kg)	293.14 ± 12.99	1350.19 ± 178.51*
Na (mg/kg)	65.07 ± 22.10	73.62 ± 5.47
B (mg/kg)	0.07 ± 0.01	0.04 ± 0.01*
Cu (mg/kg)	8.74 ± 0.52	2.46 ± 0.93*
Fe (mg/kg)	6.23 ± 0.35	4.80 ± 0.74
Zn (mg/kg)	10.33 ± 0.59	2.56 ± 0.65*
Mn (mg/kg)	25.74 ± 0.81	7.4 ± 1.01*
S (mg/kg)	8.87 ± 2.26	11.53 ± 2.11
pH	6.23 ± 0.07	5.25 ± 0.10*
Cation exchange capacity (cmol/kg)	6.97 ± 0.54	17.74 ± 3.74*
(Ca+Mg)/K ratio	8.90 ± 0.68	260.65 ± 171.55*
Mg: K ratio	1.93 ± 0.15	146.67 ± 98.82*
Na: K ratio	0.23 ± 0.08	3.75 ± 2.29*
S-value (cmol/kg)	12.73 ± 0.92	21.08 ± 2.36*
Biological soil properties		
Earthworm abundance	13.00 ± 2.60	2.29 ± 0.97*
Soil organic matter (%)	2.99 ± 0.10	0.9 ± 0.19*
Active carbon content (%)	1.75 ± 0.06	0.53 ± 0.11*
Mineralizable N (%)	62.74 ± 7.06	19.40 ± 3.90*
Bacterial feeding nematodes	1861.43 ± 636.71	111.43 ± 40.32*
Fungal feeding nematodes	100.00 ± 93.50	84.29 ± 29.51

Omnivorous nematodes	14.29 ± 6.12	12.86 ± 6.06
Predacious nematodes	10.00 ± 6.55	8.57 ± 8.57
Plant parasitic nematodes	260.00 ± 105.90	724.29 ± 165.92*
Root associated nematodes	47.14 ± 27.23	21.43 ± 12.80

4.3.3.2 Physical Soil Properties

i. Available Water Capacity (g/g):

The interaction effect between soil type and compost treatment on the available water capacity was significant (Table 11). Available water capacity was improved significantly (higher) when compost was added to degraded soil with no topsoil (Figure 27, full compost: 109.03 ± 1.90 g/g, half compost: 107.89 ± 2.30 g/g, control: 97.39 ± 2.27 g/g). The effect of adding compost to the healthy soil was non-significant.

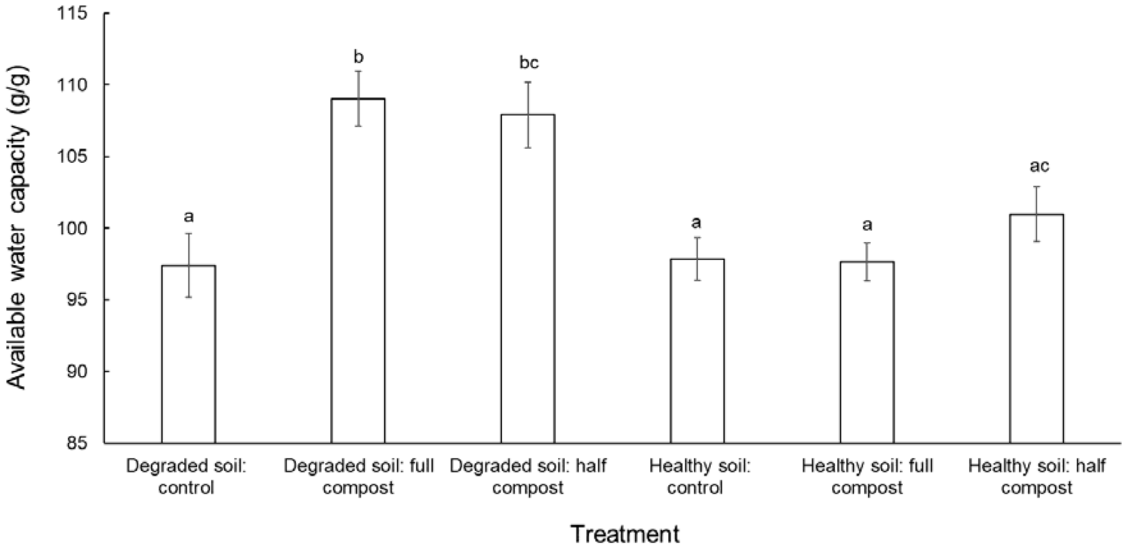

Figure 27. Means and standard error plots of the treatment effects on available water capacity.

ii. Soil Aggregate Stability (%):

There was no significant interaction effect between the treatments, but the main effect of soil type was significant (Table 12, Figure 28). Soil aggregate stability was significantly better (higher) in the healthy soil (92.56 ± 0.61 %) than in the degraded soil (88.75 ± 1.13 %). The

Welch Two Sample t-test ($t = 2.97$, d.f. $= 30.53$, p-value < 0.01) reported a significant difference.

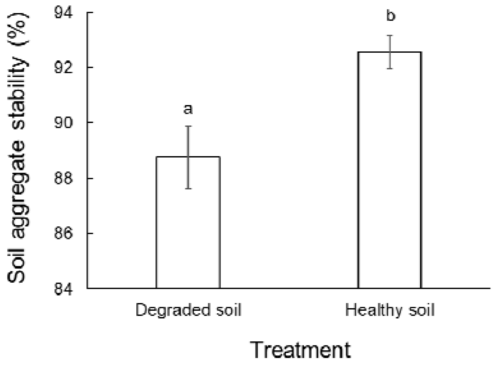

Figure 28. Means and standard error plots of the treatment effects on soil aggregate stability.

iii. *Soil Penetrability (psi):*

The interaction effect between soil type and compost treatment was significant (Table 12, Figure 29). Soil penetrability was significantly higher in the degraded soil control (3.36 ± 0.21 psi) in comparison with the healthy soil where compost was applied (Figure 3, full compost: 9.79 ± 0.52 psi, half compost: 11.64 ± 1.95 psi).

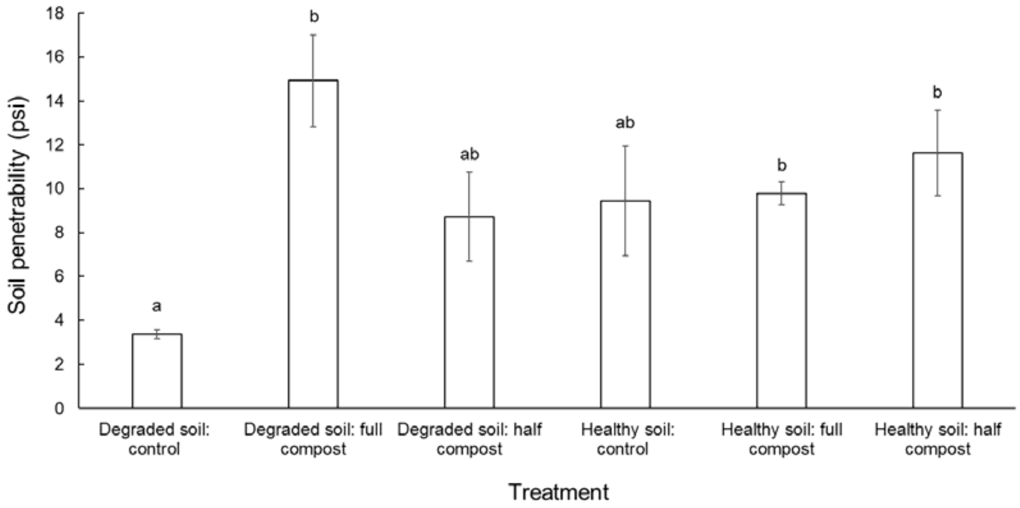

Figure 29. Means and standard error plots of the treatment effects on soil penetrability.

iv. *Bulk Density (g/cm^3):*

There was no significant interaction effect between the treatments, but the main effect of soil type was significant (Table 12, Figure 30). The Two Sample t-test (t = 9.25, d.f. = 40, *p*-value < 0.001) reported a significant difference in the bulk densities of the healthy soil (1.01 ± 0.012 g/cm^3) and the degraded soil (1.01 ± 0.01 g/cm^3).

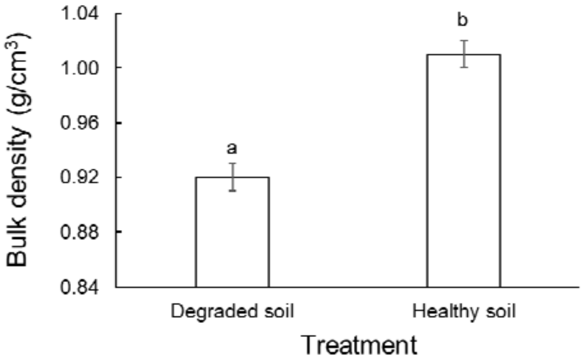

Figure 30. Means and standard error plots of the soil type effects on bulk density.

v. *Clay, Silt and Sand Content (%):*

There was no significant interaction effect on the soil clay content between the soil type and compost treatment (Table 11) and the main effect of compost was significant on healthy soil (GLZ: LR $\chi^2(2) = 7.09$; *p*-value = 0.03), but not on degraded soil (LM: SS = 50.67, d.f. = 2, *F*-value = 1.27, *p*-value = 0.31). On healthy soil, the clay content was significantly reduced from 43.51 ± 0.73 % to 39.24 ± 0.64 % after full compost treatment (Figure 31).

There was no significant interaction effect on the soil silt between the soil type and compost treatment (Table 12). Silt content differed significantly between soil types (Welch Two Sample t-test: $t_{(26.17)} = -4.28$, *p*-value < 0.001). The main effect of compost on silt % was significant on healthy soil (LM: SS = 38.10, d.f. = 2, *F*-value = 5.22, *p*-value < 0.05), and on degraded soil (LM: SS = 186.95, d.f. = 2, *F*-value = 3.58, *p*-value = 0.05). On healthy soil, the silt content was significantly reduced from 13.86 ± 0.59 % to 11.00 ± 0.53 % after full compost treatment and on degraded soil from 22.86 ± 2.43 % to 17.00 ± 1.69 % after full compost treatment and from 22.86 ± 2.43 % to 16.14 ± 1.55 % after half compost treatment (Figure 31).

There was no significant interaction effect on the soil sand between the soil type and compost treatment (Table 12). The main effect of compost on the percentage sand was significant on healthy soil (LM: SS = 178.73, d.f. = 2, *F*-value = 6.26, *p*-value < 0.01), and here the sand content was significantly increased from 42.63 ± 0.73 % to 49.76 ± 0.88 % after full compost treatment (Figure 31).

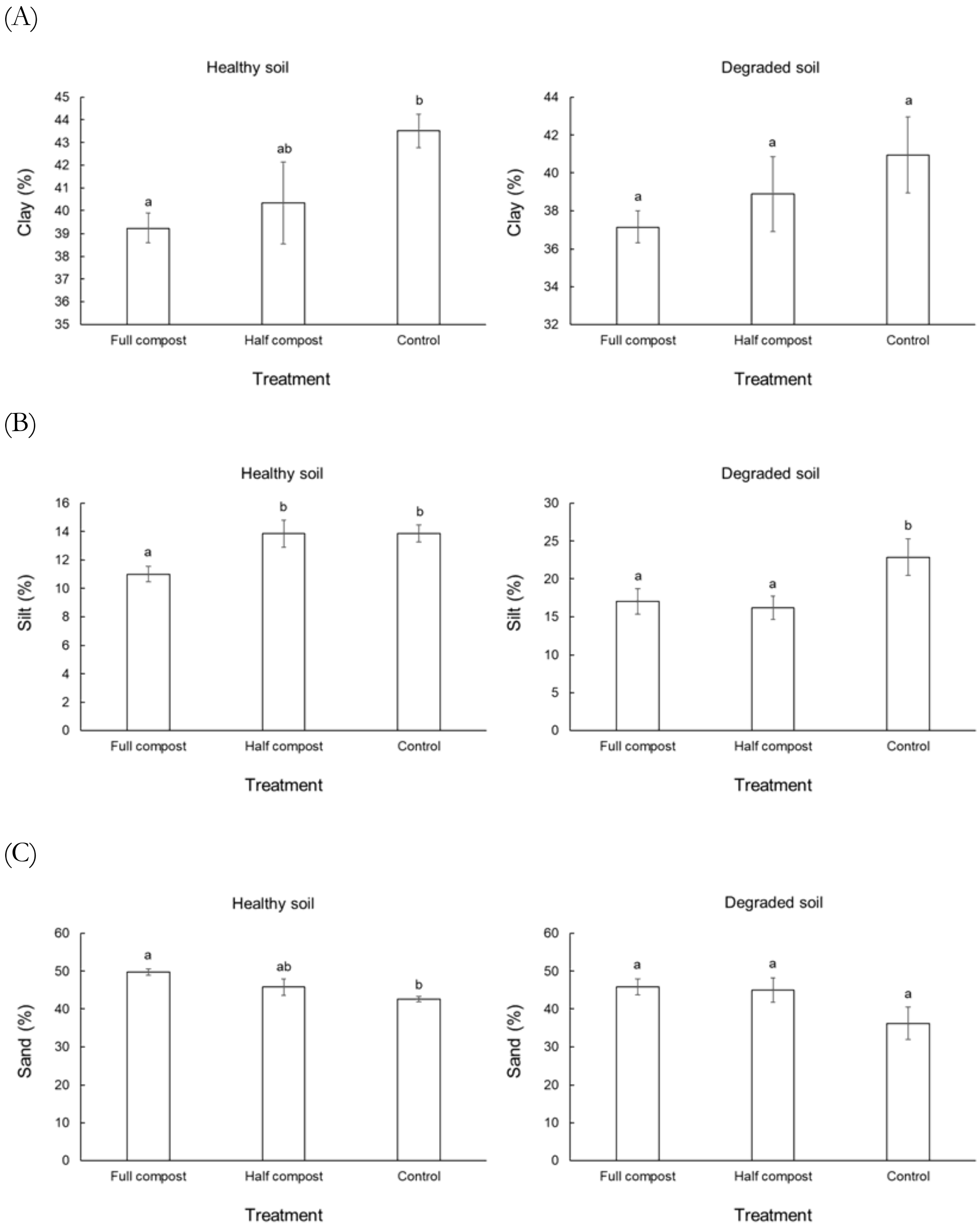

Figure 31. Means and standard error plots of (A) clay, (B) silt and (C) sand levels following compost applications on healthy and degraded soil.

4.3.3.3 Chemical Soil Properties

i. Exchangeable Macronutrients:

Potassium (K)

There was no significant interaction effect between the soil type and compost treatment on K levels in the soil (Table 12). The main effect of compost on K levels was significant in healthy soil (LM: SS = 572.24, d.f. = 2, *F*-value = 26.58, *p*-value < 0.0001) and on degraded soil (GLZ: LR $\chi^2(2) = 27.98$; *p*-value < 0.0001). The main effect of soil type was not significant (Kruskal-Wallis rank sum test: $\chi^2(20) = 20.00$, *p*-value = 0.97).

Sulphur (S)

There was no significant interaction effect between the soil type and compost treatment on S-levels in the soil (Table 12). The main effect of compost on S levels was significant in healthy soil (LM: SS = 0.65, d.f. = 2, *F*-value = 19.62, *p*-value < 0.0001) and on degraded soil (GLZ: LR $\chi^2(2) = 9.95$; *p*-value < 0.05). The main effect of soil type was not significant (Kruskal-Wallis rank sum test: $\chi^2(20) = 20.00$, *p*-value = 0.46).

Calcium (Ca)

There was no significant interaction effect between the soil type and compost treatment on Ca levels in the soil (Table 12). The main effect of compost on Ca levels was significant in healthy soil (GLZ: LR $\chi^2(2) = 20.05$; *p*-value < 0.0001) and on degraded soil (LM: SS = 2.75, d.f. = 2, *F*-value = 4.67, *p*-value < 0.05). The main effect of soil type was not significant (Kruskal-Wallis rank sum test: $\chi^2(20) = 20.00$, *p*-value = 0.46).

Magnesium (Mg)

There was no significant interaction effect between the soil type and compost treatment on Mg levels in the soil (Table 12). The main effect of soil type was not significant (Kruskal-Wallis rank sum test: $\chi^2(20) = 20.00$, *p*-value = 0.46). The main effect of compost on Mg levels was significant in healthy soil (LM: SS = 0.20, d.f. = 2, *F*-value = 19.34, *p*-value < 0.0001) but not on degraded soil (LM: SS = 0.34, d.f. = 2, *F*-value = 0.76, *p*-value = 0.48).

Phosphorous (P)

There was no significant interaction effect between the soil type and compost treatment on P levels in the soil (Table 12). The main effect of compost was significant on healthy soil (GLZ: LR $\chi^2(2) = 40.70$; *p*-value < 0.0001) and on degraded soil (GLZ: LR $\chi^2(2) = 13.51$; *p*-value < 0.01). The main effect of soil type was not significant (Kruskal-Wallis rank sum test: $\chi^2(15) = 19.39$, *p*-value = 0.20). All applications of compost on healthy soil and degraded soil significantly increased the P levels (Figure 32). In healthy soil, the P levels became toxic to the soil after compost application. It rose from 28.49 ± 3.54 mg/kg to 157.66 ± 35.59 mg/kg after a half compost application and to 254.78 ± 24.91 mg/kg after a full compost application (Figure 31). In degraded soil, the P levels rose from 1.38 ± 0.38 mg/kg to 77.84 ± 20.36 mg/kg after a half compost application and to 135.48 ± 39.95 mg/kg after a full compost application. When we consider the correlations between soil P and physical soil characteristics, we found that P correlated significantly with soil penetrability (r = 0.35, *p*-value < 0.01), clay % (r = -0.45, *p*-value < 0.001), silt % (r = -0.55, *p*-value < 0.001) and sand % (r = 0.56, *p*-value < 0.0001). The significant correlations between P, pH, S and Zn in the degraded soil and the healthy soil is plotted in Figure 33. These were all significant correlations, except for the correlation between pH and S in healthy soil.

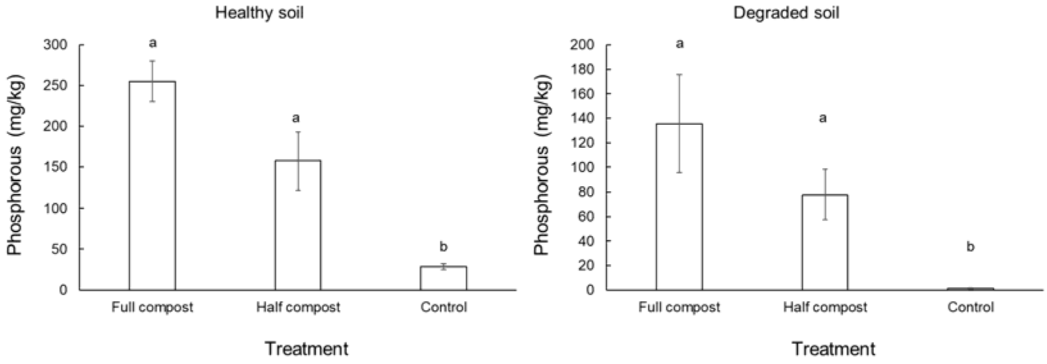

Figure 32. Means and standard error plots of soil phosphate levels following compost applications on healthy soil and degraded soil.

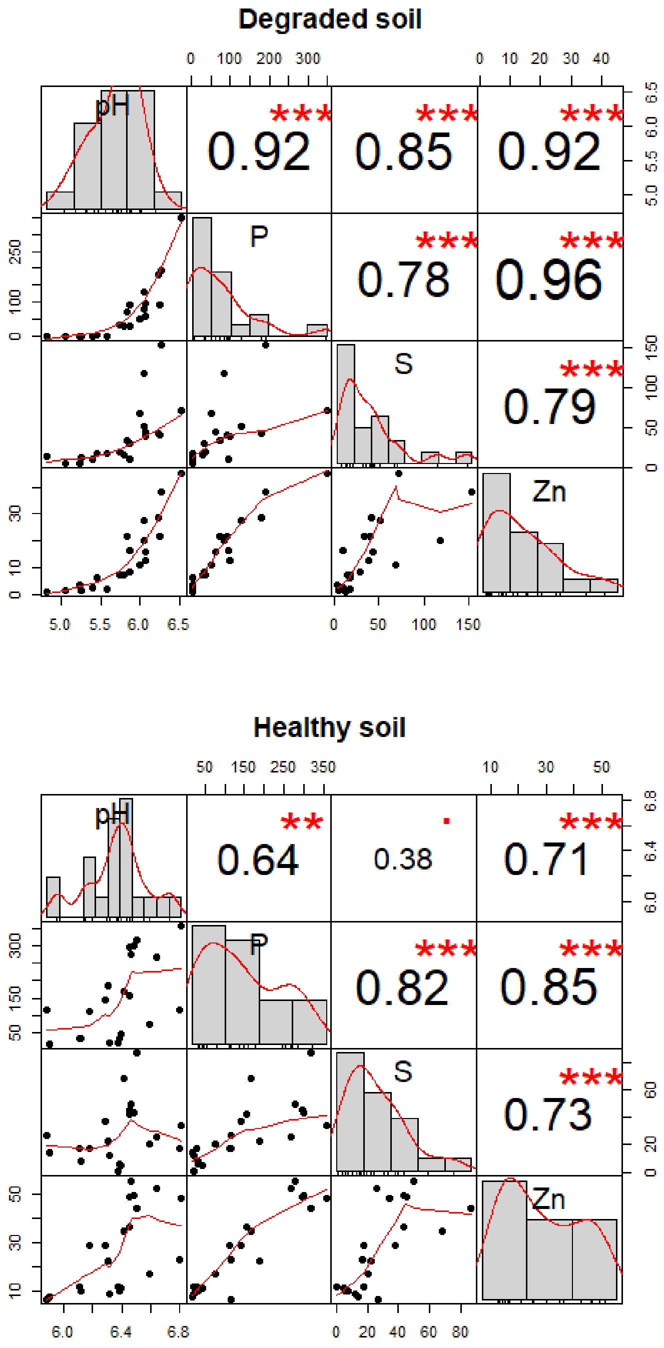

Figure 33. Correlation matrix showing the correlation and significance level of the correlation. Significance codes: *** *p*-value < 0.001; ** *p*-value < 0.01; * *p*-value < 0.05; · *p*-value < 0.1.

Soil P significantly correlated with the exchangeable K (r = 0.80, *p*-value < 0.001), exchangeable Mg (r = -0.54, *p*-value < 0.001) and exchangeable Na (r = 0.62, *p*-value < 0.001) cations. The correlation between soil P and micronutrient content of the soil was significant in all cases: Fe (r = 0.44, *p*-value < 0.01), Mn (r = 0.88, *p*-value < 0.001), Cu (r = -0.75, *p*-value < 0.001), Zn (r = 0.93, *p*-value < 0.001), B (r = 0.92, *p*-value < 0.001) and Na (r = 0.61, *p*-value < 0.001). The correlation between soil P and macro nutrient content of the soil was significant in all cases, except for Mg: Mineralizable N (r = 0.45, *p*-value < 0.01), K (r = 0.94, *p*-value < 0.001), S (r = 0.72, *p*-value < 0.001) and Ca (r = 0.56, *p*-value < 0.001).
The cation exchange capacity did not correlate with P significantly (r = -0.22, *p*-value > 0.05). There were significant correlations between the (Ca+Mg)/K ratio (r = -0.81, *p*-value < 0.001), Mg: K ratio (r = -0.72, *p*-value < 0.001), Na: K ratio (r = -0.43, *p*-value < 0.01), S-value (r = 0.35, *p*-value < 0.05) and soil P value.

ii. pH:

The interaction effect between soil type and compost treatment on the soil pH was significant (Table 12). The pH levels were higher when compost was applied; however, the multiple comparison test showed no significant increases within soil type, but across soil types. The full compost treatment on healthy soil resulted in a pH of 6.48 ± 0.03 which was significantly higher than the half compost treatment to degraded soil (pH = 5.97 ± 0.08) and all compost treatments on healthy soil increased the pH significantly in comparison to the degraded soil control (Figure 34).

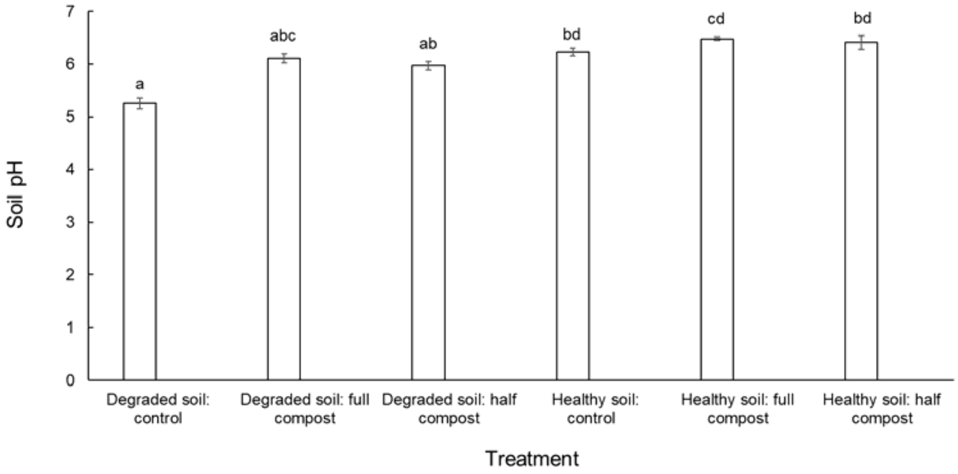

Figure 34. Means and standard error plots of soil pH levels following compost applications on healthy soil and degraded soil where the interaction effect between the treatments were significant.

iii. Micronutrient Concentrations:

The interaction effect between soil type and compost treatment on the soil Fe content was significant (Table 11). The Fe levels increased significantly after a full compost treatment in both soil types (healthy soil: from 6.23 ± 0.35 to 11.87 ± 0.78 mg/kg; degraded soil: from 4.80 ± 0.74 to 13.62 ± 0.65 mg/kg). It also increased significantly after a half compost application in degraded soil (14.90 ± 1.78 mg/kg) relative to the control groups in all soil types and half compost treatment in healthy soil (Figure 35).

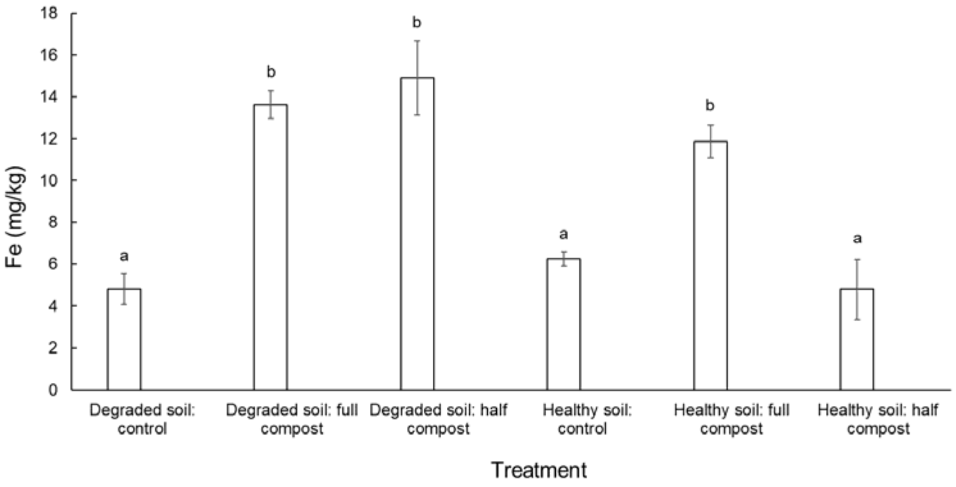

Figure 35. Means and standard error plots of soil Fe levels following compost applications on healthy soil and degraded soil where the interaction effect between the treatments were significant.

The interaction effect between soil type and compost treatment on the soil Mn content was not significant (Table 11). Mn content differed significantly between soil types (Two Sample t-test: $t_{(40)} = 2.83$, *p*-value < 0.01). The main effect of compost on Mn content was significant on healthy soil (LM: SS = 2254.30, d.f. = 2, *F*-value = 11.47, *p*-value < 0.001), and on degraded soil (LM: SS = 0.34, d.f. = 2, *F*-value = 12.05, *p*-value < 0.001). On healthy soil, the Mn content was significantly higher after a full compost application (51.06 ± 2.51 mg/kg) than after a half compost application (36.89 ± 5.93 mg/kg). On degraded soil, the Mn content was significantly elevated from 7.40 ± 1.01 to 37.87 ± 6.12 mg/kg after full compost application and to 27.26 ± 4.59 mg/kg after a half compost application (Figure 36).

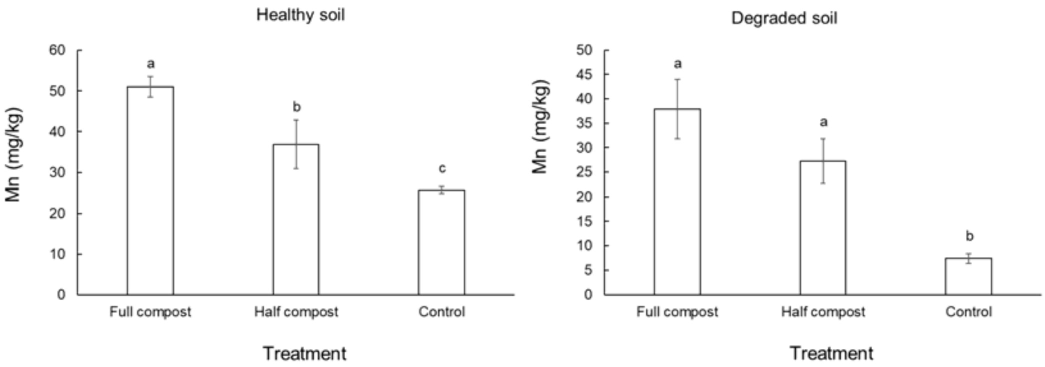

Figure 36. Means and standard error plots of soil Mn levels following compost applications on healthy soil and degraded soil.

The interaction effect between soil type and compost treatment on the soil Cu content was significant (Table 12). The Cu levels were significantly lower after a full and half compost treatment relative to the control in healthy soil (full compost application: 2.09 ± 0.32; half compost treatment: 2.35 ± 0.90 mg/kg) (Figure 37).

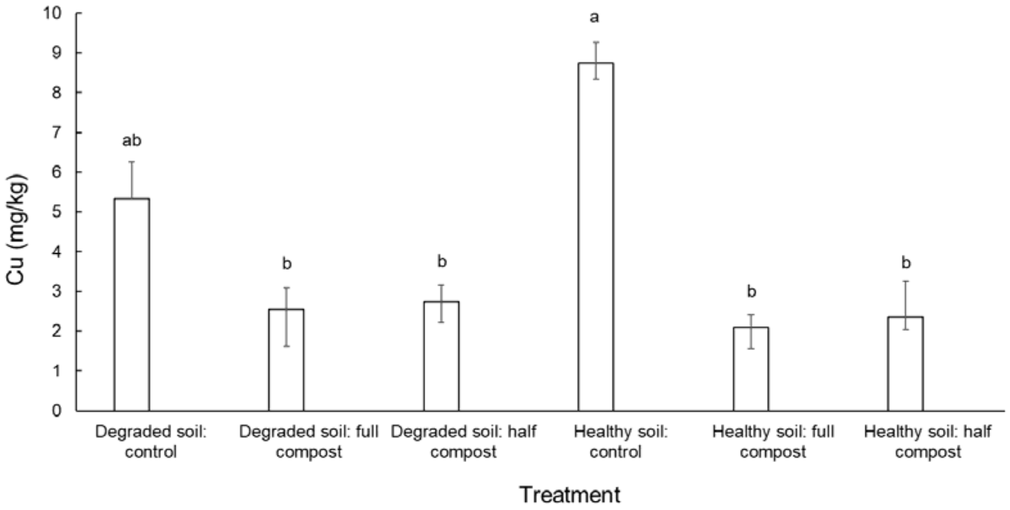

Figure 37. Means and standard error plots of soil Cu levels following compost applications on healthy soil and degraded soil where the interaction effect between the treatments was significant.

The interaction effect between soil type and compost treatment on the soil Zn content was not significant (Table 12). Zn content did not differ significantly between soil types (Kruskal-Wallis rank sum test: $\chi^2(20) = 20.00$, p-value = 0.46). The main effect of compost on Mn content was significant on healthy soil (GLZ: LR $\chi^2(2) = 59.21$; *p*-value < 0.0001), and on degraded soil (GLZ: LR $\chi^2(2) = 21.37$; *p*-value < 0.0001). Full compost applications significantly increased soil Zn levels relative to the control in each soil type (healthy soil: 45.77 ± 2.95 mg/kg; degraded soil: 24.64 ± 4.92 mg/kg) and a half compost application also increased the Zn levels significantly relative to the control (15.67 ± 3.16 *vs.* 2.56 ± 0.65 mg/kg) in degraded soil (Figure 38).

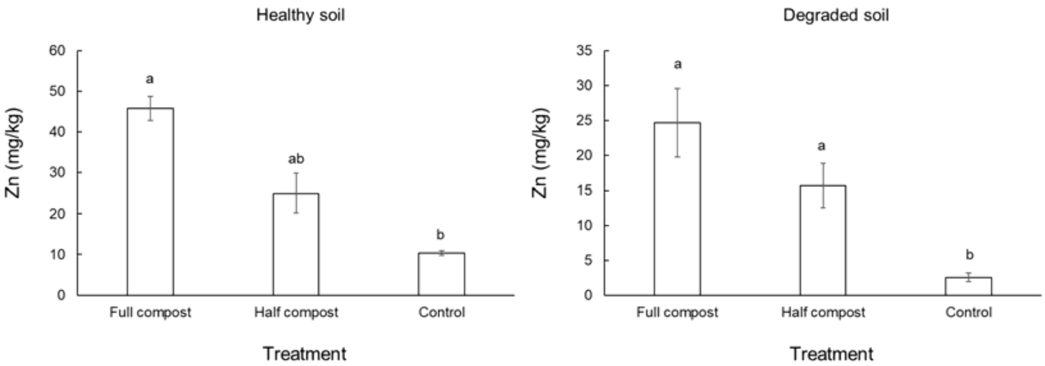

Figure 38. Means and standard error plots of soil Zn levels following compost applications on healthy soil and degraded soil.

The interaction effect between soil type and compost treatment on the soil B content was not significant (Table 12). The B content did not differ significantly between soil types (Kruskal-Wallis rank sum test: $\chi^2(11) = 14.56$, *p*-value = 0.20). The main effect of compost on B content was significant on healthy soil (LM: SS = 0.26, d.f. = 2, *F*-value = 18.60, *p*-value < 0.001), and on degraded soil (GLZ: LR $\chi^2(2) = 11.77$; *p*-value < 0.01). All compost applications significantly increased soil B levels relative to the control in each soil type (healthy soil, full compost: 0.32 ± 0.03 mg/kg; healthy soil, half compost: 0.30 ± 0.04 mg/kg; degraded soil, full compost: 0.17 ± 0.04 mg/kg, degraded soil, half compost: 0.16 ± 0.03 mg/kg (Figure 39). The interaction effect between soil type and compost treatment on the soil Na content was significant (Table 12). The Na levels were significantly higher after a full compost treatment on degraded soil (381.60 ± 38.65 mg/kg) relative to the control both soil types and the half compost treatments on degraded soil (249.56 ± 26.06 mg/kg) resulted in a significantly higher Na levels than in the healthy soil control (Figure 40).

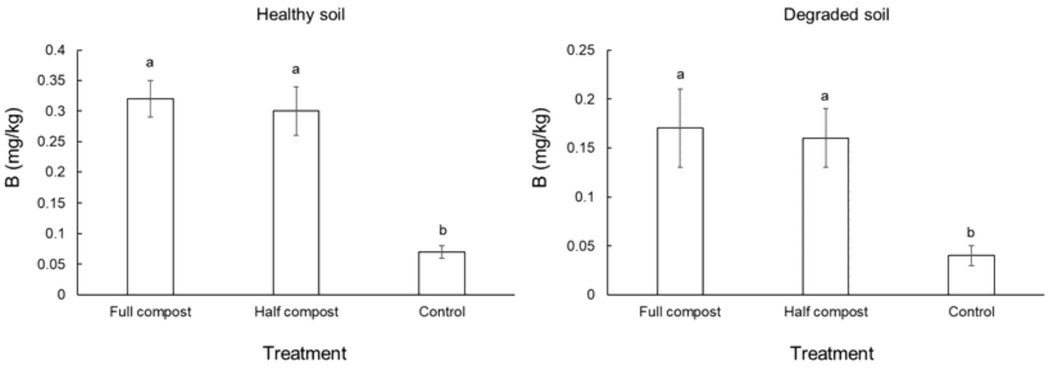

Figure 39. Means and standard error plots of soil B levels following compost applications on healthy soil and degraded soil.

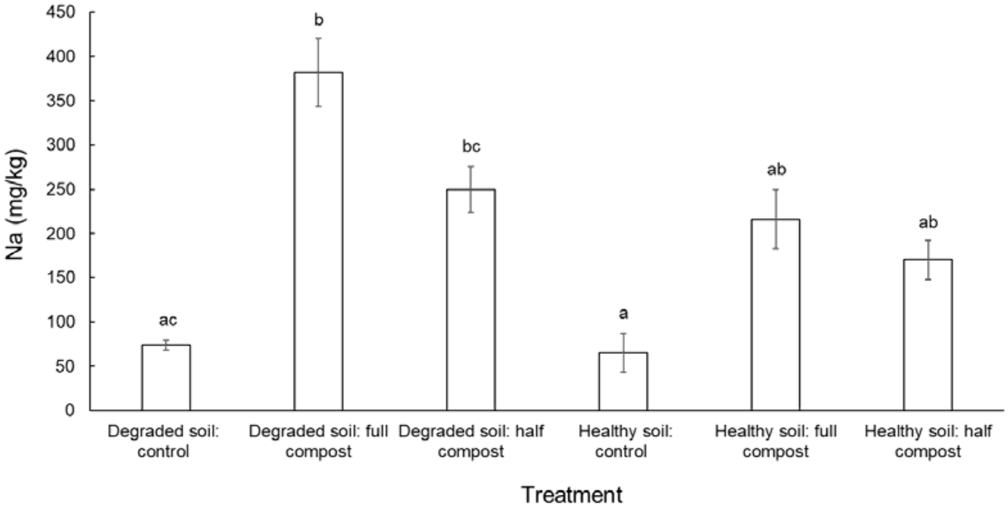

Figure 40. Means and standard error plots of soil Na levels following compost applications on healthy soil and degraded soil where the interaction effect between the treatments was significant.

iv. Cation Exchange Capacity:

The interaction effect between soil type and compost treatment on the cation exchange capacity was not significant (Table 12). There was no significant difference between the cation exchange capacities of the soil types (Kruskal-Wallis rank sum test: $\chi^2(20) = 20.00$, *p*-value = 0.46). There was no significant compost treatment effect on any soil type.

v. Cation Ratios:

The interaction effect between soil type and compost treatment on the cation exchange capacity, the Mg: K ratio and Na: K ratio was not significant (Table 12). There was no significant interaction effect between the soil type and compost treatment on the S-value (Table 34), however, the compost treatment was significant on healthy soil (LM: SS = 6.11, d.f. = 2, *F*-value = 18.06, *p*-value < 0.001) and on degraded soil (LM: SS = 3.81, d.f. = 2, *F*-value = 5.22, *p*-value < 0.05). All compost applications significantly increased the S-values relative to the control in each soil type (healthy soil, full compost: 21.55 ± 1.12 mg/kg; healthy soil, half compost: 25.66 ± 2.27 mg/kg; degraded soil, full compost: 30.21 ± 2.17 mg/kg, degraded soil, half compost: 30.01 ± 2.31 mg/kg (Figure 41).

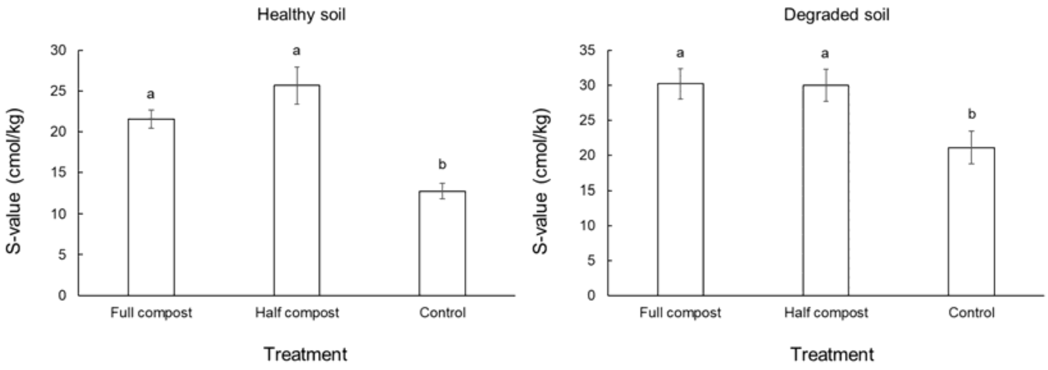

Figure 41. Means and standard error plots of the S-values following compost applications on healthy soil and degraded soil.

4.3.3.4 Biological Soil Properties

i. Earthworm Abundance:

The interaction effect between soil type and compost treatment on the earthworm abundance was not significant (Table 12). The earthworm counts did not differ significantly between soil types (Kruskal-Wallis rank sum test: $\chi^2(18) = 18.67$, *p*-value = 0.41). The main effect of compost on earthworm count was significant on healthy soil (GLZ: LR $\chi^2(2) = 49.06$; *p*-value < 0.0001), and on degraded soil (GLZ: LR $\chi^2(2) = 6.53$; *p*-value = 0.04). Full compost applications significantly increased earthworm counts relative to the control in healthy soil (107.71 ± 12.88 earthworms counted / 0.25m^2) (Figure 42).

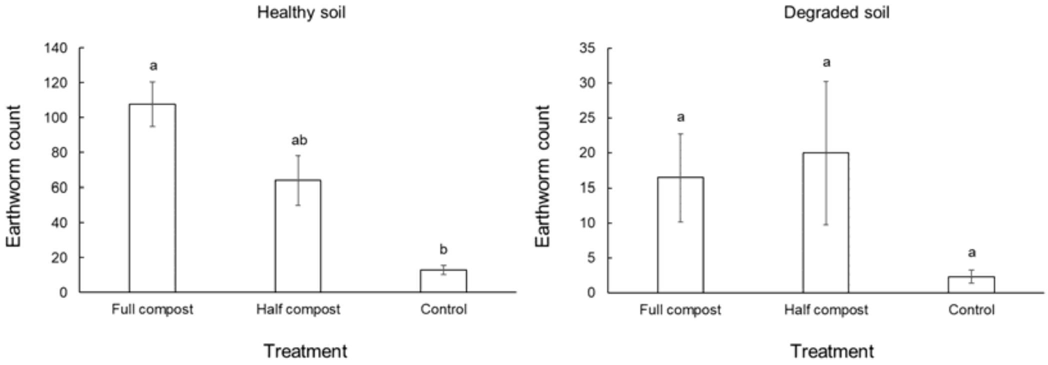

Figure 42. Means and standard error plots of the number of earthworms counted per $0.25m^2$ following compost applications on healthy soil and degraded soil.

ii. Soil Organic Matter Content (%):

The interaction effect between soil type and compost treatment on the organic matter content of the soil was significant (Table 11). All compost treatments in the healthy soil type control had significantly higher organic matter contents than the degraded soil control (Figure 43). Moreover, the half compost application resulted in a significantly higher organic matter content when applied to healthy soil (3.51 ± 0.26 %) in comparison to the same application done to degraded soil (2.17 ± 0.35 %). The full compost application resulted in 2.59 ± 0.29 % organic matter in the degraded soil and the full compost application in the healthy soil resulted to 3.12 ± 0.16 % organic matter.

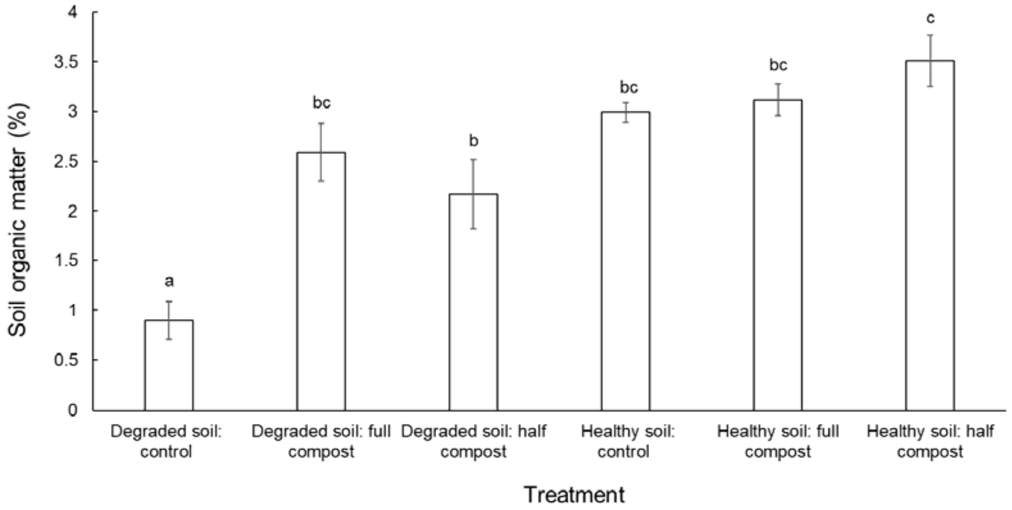

Figure 43. Means and standard error plots of soil organic matter following compost applications on healthy soil and degraded soil where the interaction effect between the treatments was significant.

iii. Active Carbon Content (%):

The interaction effect between soil type and compost treatment on the active carbon content of the soil was significant (Table 11). All compost treatments across soil type and the healthy soil type control had significantly higher active carbon contents than the degraded soil control (Figure 44). Moreover, the half compost application resulted in a significantly higher active carbon content when applied to healthy soil (2.05 ± 0.15 %) in comparison to the same application done to degraded soil (1.27 ± 0.21 %). The full compost application resulted in 1.51 ± 0.17 % active carbon in the degraded soil and the full compost application in the healthy soil resulted in 1.82 ± 0.09 % active carbon.

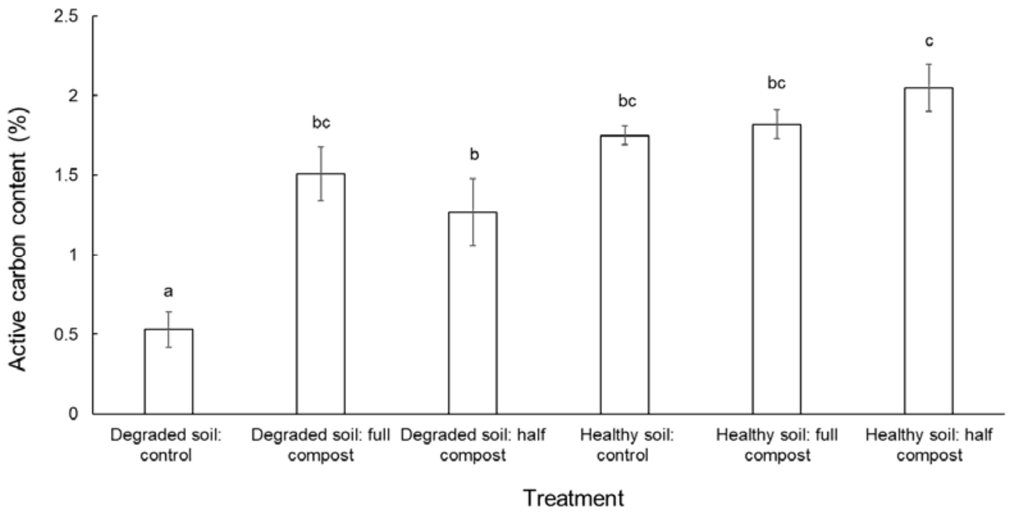

Figure 44. Means and standard error plots of the active carbon content of the soil following compost applications on healthy soil and degraded soil where the interaction effect between the treatments was significant.

iv. Potentially Mineralizable Nitrogen:

The interaction effect between soil type and compost treatment on the potentially mineralizable nitrogen was not significant (Table 12). The potentially mineralizable nitrogen did not differ significantly between soil types (Kruskal-Wallis rank sum test: $\chi^2(20) = 20$, *p*-value = 0.46). The main effect of compost on potentially mineralizable nitrogen was not significant in healthy soil (GLZ: LR $\chi^2(2) = 2.76$; *p*-value = 0.25). On degraded soil, the effect of compost was significant (GLZ: LR $\chi^2(2) = 7.30$; *p*-value < 0.05). A full compost application significantly increased the potentially mineralizable nitrogen level relative to the control (79.47 ± 17.03 %) (Figure 45).

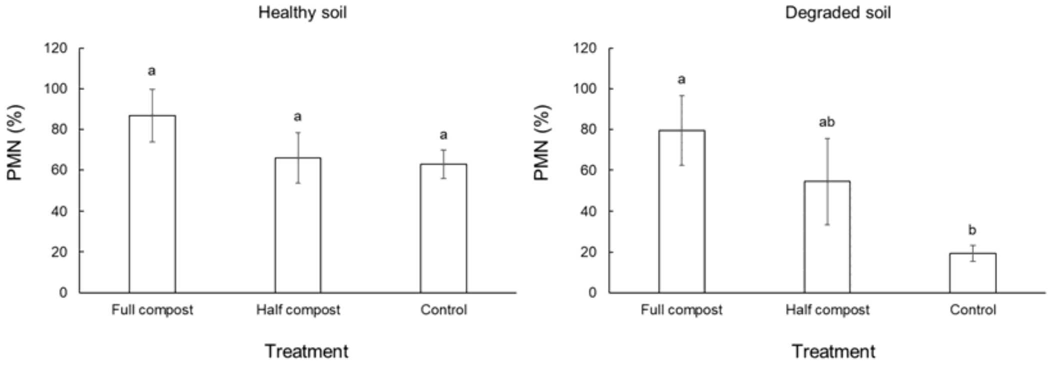

Figure 45. Means and standard error plots of the potentially mineralizable nitrogen (PMN) following compost applications on healthy soil and degraded soil.

v. Nematode Populations:

The interaction effect between soil type and compost treatment on the bacterial feeders was not significant (Table 12). The bacterial feeder count did not differ significantly between soil types (Kruskal-Wallis rank sum test: $\chi^2(20) = 20$, *p*-value = 0.46). The main effect of compost on the bacterial feeder count was not significant in healthy soil (GLZ: LR $\chi^2(2) = 4.47$; *p*-value = 0.11). On degraded soil, the effect of compost was significant (GLZ: LR $\chi^2(2) = 23.23$; *p*-value < 0.0001). A full compost application significantly increased the bacterial feeder count relative to the control (770.00 ± 227.05, Figure 46).

The interaction effect between soil type and compost treatment on the fungal feeders, omnivores and predators was not significant (Table 12), and not any main effects of the treatments. The calculated *p*-values (Chi-squared = 20, d.f. = 4, *p*-value=0.0003) showed significant outcomes of the main effects of soil type and compost treatment on the groups identified by the weighted nematode faunal analysis. From the categorical groupings, it was evident that all compost applications improved the nematode composition (Table 13), changing the outcome from 'acceptable' in healthy soil to 'desirable' and from 'moderately undesirable' to 'acceptable' in degraded soil.

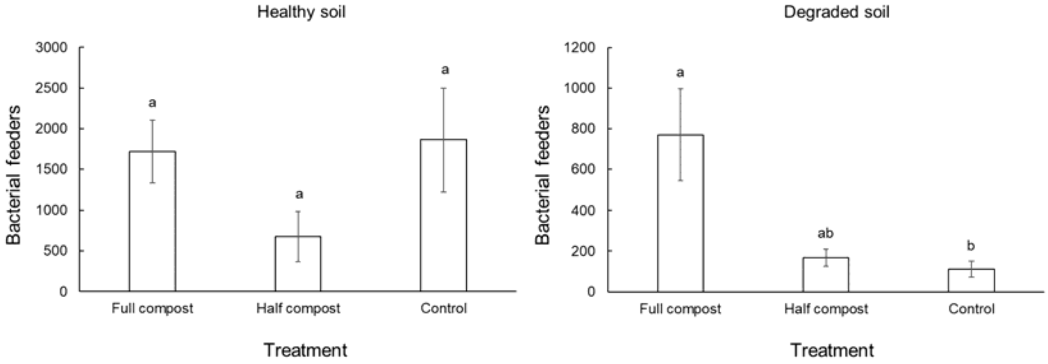

Figure 46. Means and standard error plots of the number of bacterial feeder nematodes counted per $0.25m^2$ following compost applications on healthy soil and degraded soil.

Table 11 Summary of the linear model results with dependent variables specified. The sum of squares (SS), degrees of freedom (d.f.), *F*-value and *P*-values of the model parameters are shown.

Parameter	**SS**	**d.f.**	***F*-value**	***P*-value**
Dependant variable: Available Water Capacity (g/g)				
Soil Type	372.62	1	14.74	< 0.001
Compost Treatment	374.19	2	7.40	< 0.01
Soil Type × Compost Treatment	250.99	2	4.96	< 0.05
Residuals	910.38	36		
Dependant variable: Clay (%)				
Soil Type	43.45	1	2.92	0.10
Compost Treatment	117.47	2	3.95	0.03
Soil Type × Compost Treatment	2.14	2	0.07	0.93
Residuals	535.54	36		
Dependant variable: Sand (%)				
Soil Type	145.90	1	3.16	0.08
Compost Treatment	522.82	2	5.66	0.01
Soil Type × Compost Treatment	55.29	2	0.60	0.56
Residuals	1662.50	36		
Dependant variable: Fe (mg/kg)				
Soil Type	126.99	1	15.77	< 0.001
Compost Treatment	370.10	2	22.97	< 0.001
Soil Type × Compost Treatment	249.00	2	15.46	< 0.001
Residuals	289.98	36		
Dependant variable: Mn (mg/kg)				
Soil Type	1976.50	1	16.66	< 0.001
Compost Treatment	5470.20	2	23.06	< 0.001

Soil Type × Compost Treatment	134.50	2	0.57	0.57
Residuals	4270.70	36		
Dependant variable: S-value (cmol/kg)				
Soil Type	532.15	1	19.92	< 0.001
Compost Treatment	951.56	2	17.81	< 0.001
Soil Type × Compost Treatment	40.48	2	0.78	0.48
Residuals	961.73	36		
Dependant variable: Soil organic matter (%)				
Soil Type	18.26	1	44.28	< 0.0001
Compost Treatment	7.57	2	9.18	< 0.001
Soil Type × Compost Treatment	4.28	2	5.19	< 0.05
Residuals	14.84	36		
Dependant variable: Active carbon content (%)				
Soil Type	6.25	1	44.31	< 0.0001
Compost Treatment	2.60	2	9.21	< 0.001
Soil Type × Compost Treatment	1.46	2	5.19	< 0.05
Residuals	5.08	36		

Table 12 Summary of the generalized linear model results with dependent variables specified. The chi-square (χ^2) statistic, degrees of freedom (d.f.) and *P*-values of the model parameters are shown.

Parameter	χ^2	**d.f.**	***p*-value**
Dependant variable: Bulk Density (g/cm^3)			
Soil Type	80.33	1	< 0.001
Compost Treatment	0.84	2	0.66
Soil Type × Compost Treatment	0.68	2	0.71
Dependant variable: Soil Penetrability (psi)			
Soil Type	0.78	1	0.38
Compost Treatment	11.52	2	< 0.01
Soil Type × Compost Treatment	0.68	2	< 0.01
Dependant variable: Soil Aggregate Stability (%)			
Soil Type	8.94	1	< 0.01
Compost Treatment	2.73	2	0.26
Dependant variable: Phosphate (mg/kg, Bray I)			
Soil Type	13.15	1	< 0.001
Compost Treatment	50.11	2	< 0.0001
Soil Type × Compost Treatment	3.28	2	0.19
Dependant variable: Silt (%)			
Soil Type	23.44	1	< 0.0001

Compost Treatment	9.81	2	< 0.001
Soil Type × Compost Treatment	5.32	2	0.07
Dependant variable: pH (KCl analysis method)			
Soil Type	70.91	1	< 0.0001
Compost Treatment	46.85	2	< 0.0001
Soil Type × Compost Treatment	14.67	2	< 0.0001
Dependant variable: Cu (mg/kg)			
Soil Type	2.64	1	0.10
Compost Treatment	68.30	2	< 0.0001
Soil Type × Compost Treatment	11.85	2	< 0.01
Dependant variable: Zn (mg/kg)			
Soil Type	21.92	1	< 0.0001
Compost Treatment	74.37	2	< 0.0001
Soil Type × Compost Treatment	4.79	2	0.09
Dependant variable: B (mg/kg)			
Soil Type	18.70	1	< 0.0001
Compost Treatment	45.96	2	< 0.0001
Soil Type × Compost Treatment	4.23	2	0.12
Dependant variable: Cation exchange capacity (cmol/kg)			
Soil Type	14.67	1	< 0.001
Compost Treatment	4.12	2	0.13
Soil Type × Compost Treatment	5.29	2	0.07
Dependant variable: (Ca+Mg)/K ratio			
Soil Type	2.64	1	0.10
Compost Treatment	4.13	2	0.13
Soil Type × Compost Treatment	3.86	2	0.15
Dependant variable: Mg: K ratio			
Soil Type	2.68	1	0.10
Compost Treatment	3.90	2	0.14
Soil Type × Compost Treatment	3.80	2	0.15
Dependant variable: Na: K ratio			
Soil Type	4.10	1	0.04
Compost Treatment	3.41	2	0.18
Soil Type × Compost Treatment	3.31	2	0.19
Dependant variable: Potentially mineralizable N (mg/kg)			
Soil Type	3.43	1	0.06
Compost Treatment	9.51	2	< 0.05
Soil Type × Compost Treatment	2.10	2	0.35
Dependant variable: K (mg/kg)			
Soil Type	24.83	1	< 0.0001
Compost Treatment	73.71	2	< 0.0001

Soil Type × Compost Treatment	2.25	2	0.33
Dependant variable: Ca (mg/kg)			
Soil Type	0.51	1	0.48
Compost Treatment	27.40	2	< 0.0001
Soil Type × Compost Treatment	5.24	2	0.07
Dependant variable: Mg (mg/kg)			
Soil Type	109.01	1	< 0.0001
Compost Treatment	3.85	2	0.15
Soil Type × Compost Treatment	0.91	2	0.64
Dependant variable: Earthworm count			
Soil Type	46.94	1	< 0.0001
Compost Treatment	44.66	2	< 0.0001
Soil Type × Compost Treatment	1.76	2	0.42
Dependant variable: Bacterial feeders			
Soil Type	23.20	1	< 0.0001
Compost Treatment	9.81	2	< 0.01
Soil Type × Compost Treatment	5.56	2	0.06
Dependant variable: Fungal feeders			
Soil Type	1.19	1	0.28
Compost Treatment	3.09	2	0.21
Soil Type × Compost Treatment	2.97	2	0.23
Dependant variable: Omnivores			
Soil Type	0.38	1	0.56
Compost Treatment	1.52	2	0.47
Soil Type × Compost Treatment	1.89	2	0.39
Dependant variable: Predators			
Soil Type	2.13	1	0.15
Compost Treatment	3.10	2	0.21
Soil Type × Compost Treatment	0.33	2	0.85

4.4 Discussion

The most notable changes in the soil that took place were the significant increases in soil phosphorous content and pH which resulted not in an improvement in soil quality in terms of these two indicators but revealed an important issue about the use of compost containing animal manure originating from dairies or feedlots. A discussion follows under section *4.4.1.2.*

4.4.1 Soil Type Differences

The two soil types (healthy and degraded) were essentially the same soil but in the degraded case the topsoil was removed completely to the depth of more than 1.5 metres. More than the normal topsoil had been removed in this case which included all the organic material, seed bank and nutrient-rich upper layer of the soil. Table 9 shows the decline in almost all soil aspects which normally contribute to healthy soils, where the topsoil was removed.

4.4.1.1 Physical Soil Properties

i. Available Water Capacity (g/g):

Significant effects were seen on degraded soil, unlike in the healthy soil. The results show that compost addition onto degraded soil improved the available water capacity of the soil. The degraded soil had very little or no topsoil with organic matter to aid in retaining moisture and the compost improved this situation. The available water capacity may have increased even more in the degraded soil if the compost treatments were incorporated into the soil and not applied as a mulch only.

ii. Soil Aggregate Stability (%):

The significantly better soil aggregate stability in the healthy soil when compared to the degraded soil can be ascribed to the fact that the healthy soil was a topsoil with a good structure whereas the degraded soil was deprived of topsoil. The poor structure of the degraded soil is reflected in the low soil aggregate stability. Compost treatments did not affect any change because it had probably not been applied long enough before SAS was measured, as well as the fact that the compost was applied as a mulch and not incorporated into the soil.

iii. Soil penetrability (psi):

The higher penetrability of the degraded soil control plots as compared to the healthy soil plots with compost treatments was unexpected. Gugino et al., (2009) explain however that "the level of soil moisture can greatly affect the ease with which the probe penetrates the soil. It is recommended that penetration reading be taken when the soil is at field capacity (several days after free drainage). If the soil conditions are not ideal, it is important to note conditions at the time of measurement so proper interpretation of the reading can be made". Soil moisture content of the healthy soils was probably higher at the time of measurement than the adjacent degraded plots because the healthy soil plots would have retained water much longer after irrigation due to their higher water holding capacities, as seen in Table 10. Soil texture also changed significantly (Table 10) after removal of the topsoil where penetrability was effectively now compared between a topsoil (healthy soil) and a subsoil (degraded soil) as can be seen from Figures 23 – 25 and these changes may also explain these unexpected results where the healthy soils had higher penetrability values than the degraded soils.

iv. Bulk Density (g/cm^3):

Bulk density was lower in the healthy soil and compost treatments did not have a significant effect. This can be ascribed to the topdressing type of application applied, which lay on the soil surface as a mulch for a long time and initially only affected the surface of the soil layer. Soil samples were taken from 0 – 30 cm deep where the organic matter did not have enough time to penetrate, as compost takes a long time to have an effect if applied on the soil surface as a mulch.

v. Clay, Silt and Sand Content (%):

The soils of these trial orchards are the type known as Hutton, which are rich soils with a high clay content (37 – 43%) in this case, originating from weathered basalt and have high ion adsorbing properties. The high clay content consequently renders cations less available for plant uptake when they are adsorbed to the negatively charged clay particles. The situation is aggravated at a high pH where negative charges of clay soil particles are increased resulting in an increased adsorption of cations like Fe, rendering them unavailable for plant uptake as was witnessed in this study. Although these ions become exchangeable (and then available for plant uptake) in soils with high cation exchange capacities, they can be largely unavailable in conditions like the ones experienced in the trial plots.

Full compost treatments significantly decreased the clay and silt contents of healthy soil, this is unusual as soil texture does not normally change. The compost did however contain sand and although the quantity was not measured, it is assumed that this addition of sand through the compost must have caused the change in soil texture as was observed. The silt percentage was significantly reduced in the degraded soil after treatment, but also had a significantly higher silt content than the healthy soil initially.

4.4.1.2 Chemical Soil Properties

i. Exchangeable Macronutrients:

Potassium (K)

All applications of compost on healthy soil and degraded soil significantly increased the K levels (Figure 47). In healthy soil, the K levels were increased to 1698.53 ± 149.08 mg/kg after a full compost application and to 1479.01 ± 151.10 mg/kg after a half compost application. In degraded soil, the K levels were increased to 1221.93 ± 194.49 mg/kg after a full compost application and to 675.59 ± 179.21 mg/kg after a half compost application.

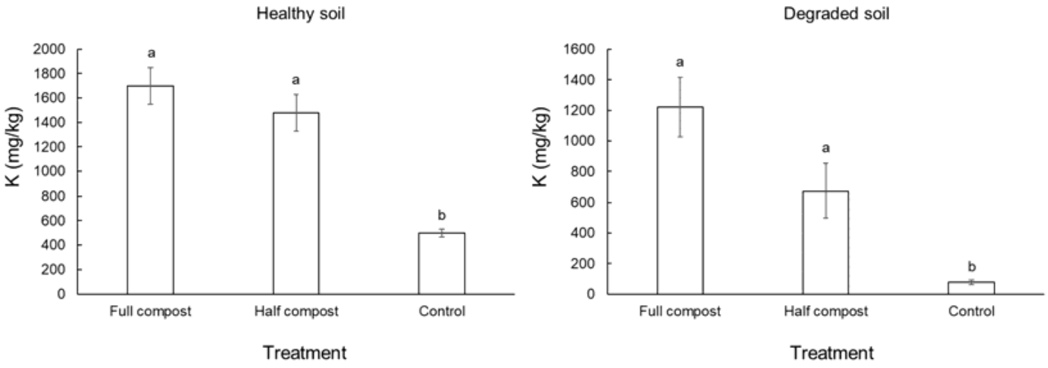

Figure 47. Means and standard error plots of the K levels following compost applications on healthy soil and degraded soil.

Sulphur (S)

All applications of compost on healthy soil significantly increased the S levels (Figure 48). On healthy soil, the S levels were increased to 51.63 ± 7.51 mg/kg after a full compost application and to 25.05 ± 3.12 mg/kg after a half compost application. In degraded soil, the S levels were significantly increased to 65.80 ± 15.61 mg/kg after a full compost application and to 39.29 ± 14.01 mg/kg after a half compost application, but the latter application was not significantly different from either the full or the control treatment.

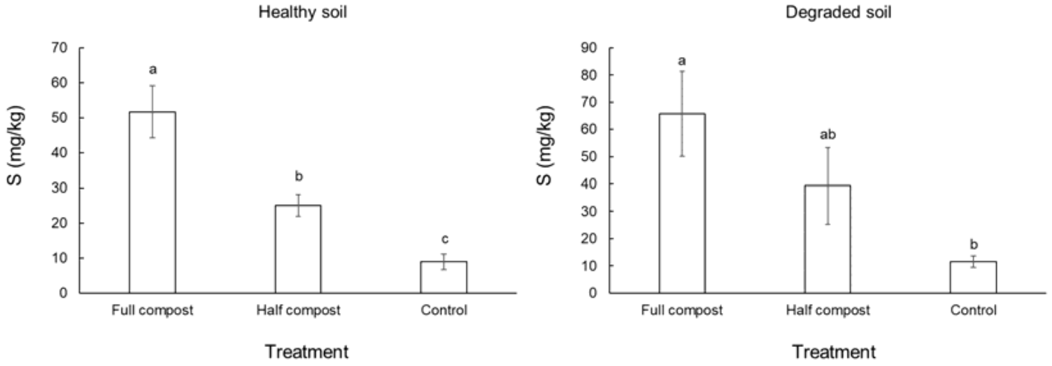

Figure 48. Means and standard error plots of the S levels following compost applications on healthy soil and degraded soil.

Calcium (Ca)

All half applications of compost significantly increased the Ca levels significantly (healthy soil: 3507.47 ± 440.06 mg/kg; degraded soil: 2715.75 ± 211.97 mg/kg). On degraded soil, the full compost application significantly increased the Ca levels relative to the control to 2599.49 ± 210.52 mg/kg (Figure 49).

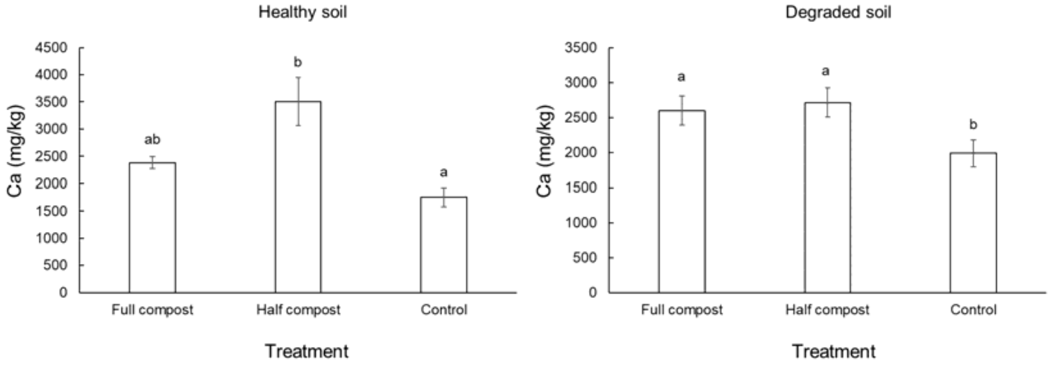

Figure 49. Means and standard error plots of the Ca levels following compost applications on healthy soil and degraded soil.

Magnesium (Mg)

All compost applications significantly increased the Mg levels relative to each other (Figure 50) and to the control on the healthy soil (full compost: 531.81 ± 29.25 mg/kg; half compost: 439.21 ± 34.95 mg/kg).

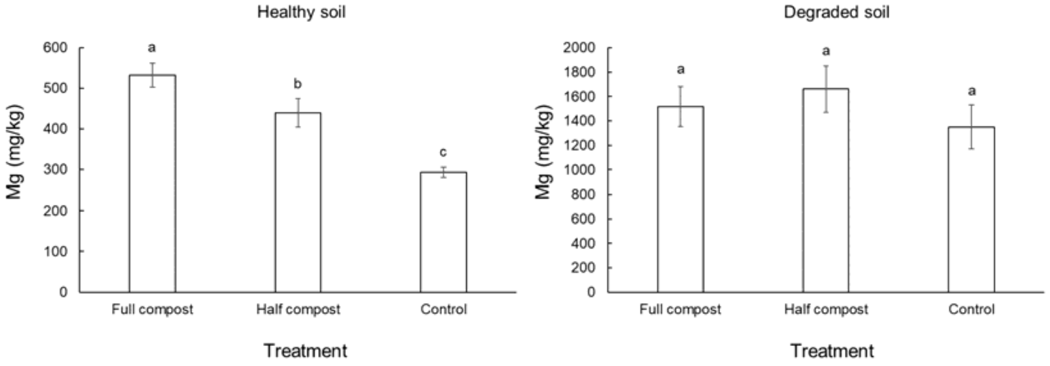

Figure 50. Means and standard error plots of the Mg levels following compost applications on healthy soil and degraded soil.

Phosphorous (P)

Compost treatments significantly increased the soil P levels to values beyond 157 mg/kg after half compost application and to 254 mg/kg after a full compost application and similarly the degraded soil P values exceeded 77 mg/kg in the half compost application and was more than 135 mg/kg in the full compost application. Recommended norms of soil P for macadamia cultivation are 30 - 75 mg/kg, for the Bray 1 analysis method (Kuperus and Abercrombie, 2003, adapted by Nortjé, 2017). The healthy soil control with a mean P content of 28.5 mg/kg was within this range before treatment (Table 9); however, the degraded soil control with a mean soil P content of 1.38 mg/kg was well below the minimum threshold of 22 mg/kg, and significantly lower than the P content of the healthy soil before treatments.

Macadamia root systems are evolutionary adapted to actively mine P from the soil (Lambers et al., 2006) and are therefore sensitive to high soil P levels. *Macadamia* spp. originated in an area in Australia with a high rainfall and highly leached soils which contain low levels of P (Stephenson et al., 2002) and consequently adapted to a relatively low P requirement. The P level of the topsoil of the trial plot soils reached toxic levels (for macadamias) after treatment with the manure containing compost. The high pH and P levels also resulted in some induced deficiencies like Iron (Fe) (Nortjé, 2017) which resulted in the leaves of the treated trees turning yellow (Figure 51).

Animal manures are reported to contain significant amounts of P (Barnett, 1994a; Dao and Hoang, 2008; Dao and Schwartz, 2010). Of the total P ingested by domestic farm animals, about 70 % is excreted and the total P content in manure varies considerably (Barnett, 1994b;) which is determined by many factors, diet being significant (Toor et al., 2005; Weiss and Wyatt, 2004). Application of animal manure and products containing animal manure often leads to P accumulating in surface soils (Hao et al., 2004; Novak and Chan, 2002; Parham et al., 2002; Reddy et al., 2000; Schröder et al., 2011; Vadas et al., 2007), not only beyond agronomic requirements but excessively in many cases (Gourley et al., 2015; Liu et al., 2007; Lugo-Ospina et al., 2005). Accurate analyses of nutrient content of manure is therefore needed prior to its use in nutrient management and to avoid over-application of P in crop fields treated with manure (Lugo-Ospina et al., 2005; Nennich et al., 2005). Compost with low manure content or without any manure would probably not have resulted in the high P levels experienced in the trials.

ii. pH:

Recommended norms for pH for macadamia cultivation is 5.5 – 6.5 (Kuperus and Abercrombie, 2003, adapted by Nortjé, 2017). The soil pH (KCl analysis method) was already high from an ideal macadamia cultivation point of view (6.23 in the healthy soil and 5.25 in the degraded soil) and the compost treatments increased these levels further.

iii. Micronutrient Concentrations:

The soil Fe levels were significantly elevated, especially in degraded soil, where both compost treatments resulted in significant results. When the pH is too high, some nutrients (especially trace elements) become unavailable to the crop and some of these manifested as induced deficiencies, as was the case with Iron (Fe); although Fe levels in the soil had increased with the compost treatments in the healthy and degraded soils, the leaves of the treated trees turned yellow (Figure 51). Although Fe is taken up into the plant and is often detected in the leaves, it is not metabolized and used as a plant nutrient when the P and pH level is high.

High P and pH induced Fe-deficiencies are not uncommon and have been documented in many other crops, e.g. grain and legume crops; Bloem and Hattingh (2016) explain that bicarbonate (HCO_3^-) develops in the soil when carbon dioxide (CO_2) reacts with water in soils when the pH is higher than 6. The CO_2 is produced by plant roots and soil microbes. Excessive applications of compost or animal manures stimulate soil micro-organisms which then produce more CO_2, which may result in the development of bicarbonate, especially where the top soil layer is compacted and prevents the escape of CO_2 into the atmosphere. Fe-deficiencies typically develop in plants under these conditions because HCO_3^- ions suppress the uptake of Fe by plants. This suppression of Fe uptake may also occur in the plants (not only in the root zone), so that leaf analyses show adequate levels of Fe in the plant, but it is physiologically inactive, resulting in the symptoms shown in Figure 51.

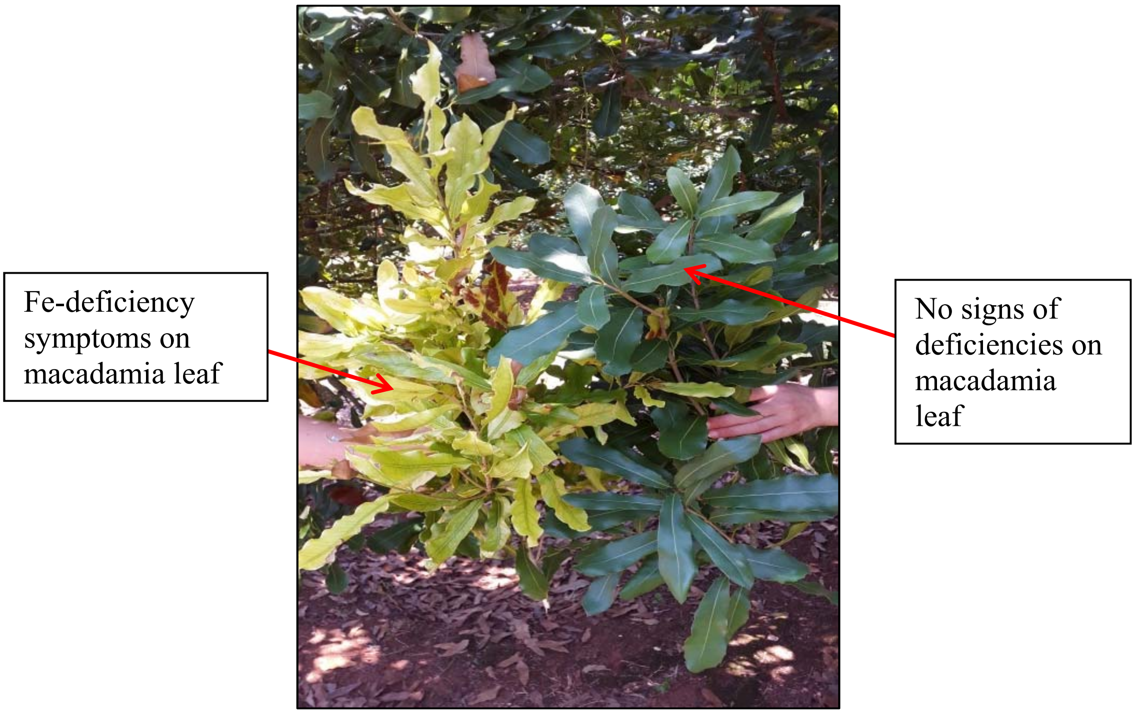

Figure 51. Comparison of leaves from the control and full compost treatment on healthy soils.

A similar type of increase as with Fe occurred with Zinc (Zn) levels in the soil that should be between a recommended 15 – 50 mg/kg (Kuperus and Abercrombie, 2003, adapted by Nortjé, 2017) but increased in the healthy soil and degraded soil and showed deficient in the leaf analyses. The Zn level in the leaf should be 15 – 50 mg/kg but it was 9 - 11 mg/kg following compost treatments.

Copper (Cu) levels should be 5 – 10 mg/kg in the soil, but, being a cation, it is affected by adsorption and high pH like the other cations. Cu however, is additionally affected by microorganisms, which utilize it in the process of decomposing organic material, after which it then becomes available. This is referred to as a Cu-negative period. This was evident when Cu levels decreased in the healthy and degraded soils after the compost treatments.

Boron (B) levels increased with the compost treatments, but not significantly; it should be at levels of 1 – 4 mg/kg for macadamia cultivation. Manganese (Mn) levels should be 100 – 1000 mg/kg and these improved significantly and *pro rata* with the compost applications in the healthy and degraded soils. Mn (also a cation) was expected to be affected by adsorption, but leaf analyses showed it to be high (up to 519 mg/kg) whereas the recommended norms for Mn is 100 – 1000 mg/kg.

iv. Cation exchange capacity:

No significant changes occurred in the soil after compost treatment.

v. Cation ratios:

Potassium (K), Sodium (Na), Calcium (Ca) and Magnesium (Mg) cannot be considered in isolation since ratios between these elements are more important than the content of each element separately. These ratios were analysed in the soil and expressed as ions and not as parts per million (ppm) or mg/kg, as was done for the nutrient elements. The focus here is, therefore, on cation ratios and milli-equivalents and not ppm. The S-value was also analysed and represents the exchangeable cations with the addition of free Hydrogen (H) ions. Na: K and Ca: Mg ratios should both be 3: 1 with the Na: K ratio required as low as possible. Ca: Mg ratios improved in all cases with compost except for the single treatment in the healthy soils. After compost treatments the percentage K increased in the healthy- and degraded soils. In the degraded soils the K levels improved to ideal levels but in the healthy soils it exceeded the ideal maximum levels of 10 %. This had a positive effect on the K ratio compared to other elements, where the Na: K ratios improved in all treatments as compared to the control sites. Similar improvements were visible in the Mg: K ratios; here the changes were more dramatic and significant, especially in the degraded soils.

Ideal Na levels should be less than 1 mg/kg, but the Na levels increased above this value due to the compost treatments. This was probably because of high mineral salt levels as is commonly found in animal manures. The recommended Sulphur (S) levels should be at least 20 mg/kg (AmAc analysis) and increased (improved) significantly in all treatments. Generally, the compost treatments improved ion ratios, although the P, Na and pH increased too much. This was a result of using a compost containing too much animal manure.

vi. Correlations

Changes in P values correlated with most other elements, which again demonstrates the complexity of soil chemistry, the intricate interrelationships of all elements, and how small changes in one element may have a significant impact on others. Changes in P correlated significantly with changes in pH, with most macronutrients (excluding Mg), with all micronutrients, and the cation ratios as well. P can perhaps be singled out as a “keystone” element which has to be managed with caution, emphasizing the need to carefully analyse any organic additions to the soil which may contain high levels of P such as was the case here with compost containing dairy manure.

4.4.1.3 Biological Soil Properties

vii. Earthworm Abundance:

Degraded soils plots had lost all the fertile topsoil and, although there were increases in earthworm numbers with the treatments, the improvement on soil conditions for earthworms that the compost treatments brought about was obviously not sufficient to result in a dramatic increase in earthworm numbers. Conversely, the compost treatments in the healthy soil plots resulted in significant increases in earthworm numbers.

viii. Soil Organic Matter Content (%):

A significantly higher increase in organic matter content was recorded in healthy soils compared to the degraded soils, which was to be expected as healthy soil plots already had high levels of organic material before the treatments, which was not the case with the degraded plots.

ix. Active Carbon Content (%):

Active carbon content responded like organic matter content for the same reasons where the healthy plots already had high levels of carbon as compared to the degraded plots.

x. Potentially Mineralizable Nitrogen (PMN):

Potentially mineralizable nitrogen responded like organic matter and active carbon as a result of the high organic matter content already present in the healthy plots, compared to very little or none in the degraded plots.

xi. Nematode populations:

Nematodes are useful indicators of soil conditions (Arantzazu et al., 2000; Zhao and Neher, 2013) and therefore deserve more attention. They are also considered good indicators of changes in soil, such as those affected by the addition of organic material (Ferris and Bongers, 2006; Neher and Olson, 1999 *in* Zhao and Neher, 2013). Table 1 in Appendix E displays how nematode populations can be ordinated in four categories or quadrats (Ferris and Bongers, 2009); Figure 1 in Appendix E displays the faunal ordination in quadrats of the nematode populations surveyed in the trial plots. The Structure Index (SI) is a measure of the number of trophic layers within the soil food web along with the potential for regulation by predators (Pattison et al., 2008). A low SI indicates a disturbed or degraded soil ecosystem while a high SI indicates structured or matured conditions (Baniyamuddin et al., 2007). The Enrichment Index (EI) is an indication of the resources available in the soil food web as well as responses by primary decomposers (such as basal nematode communities) (Pattison et al., 2008).

According to Baniyamuddin et al., (2007) nutrient enriched soil ecosystems have high EI values while systems which are nutrient depleted have low EI values.

Kapp (2013) explains that a balanced nematode community is a reliable indication of a healthy soil. Unbalanced nematode communities like those which are strongly enriched will, for example, represent soils which host too many bacteria and fungi feeders and have too few omnivores and predators. Table 1 (Appendix F) provides the analyses of each of the 7 repetitions for all treatments in the healthy and degraded soil trial plots as well as the controls. From the categorical groupings, it was evident that all compost applications improved the nematode composition (Table 13), changing the outcome from 'acceptable' in healthy soil to 'desirable' and from 'moderately undesirable' to 'acceptable' in degraded soil.

Table 13 Outcomes from the weighted nematode faunal analysis according to soil type and compost treatment.

Soil type	Treatment	Outcome
Healthy soil	Full compost	Desirable
Healthy soil	Half compost	Desirable
Healthy soil	Control	Acceptable
Degraded soil	Full compost	Acceptable
Degraded soil	Half compost	Acceptable
Degraded soil	Control	Moderately undesirable

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

From my thesis statement for this study, I intended to demonstrate that agroecological conversions which are mediated by the application of supplementary cover crops with the aim of serving a dual trap and cover crop purpose, may contribute significantly in achieving the goal of ecosystem conformity in sub-tropical fruit orchards, demonstrated here as a step in the conversion process of conventionally managed macadamia orchards to fully sustainable agroecosystems.

5.2 Conclusion

5.2.1 Crop Protection Trials

The significance of these results is that both treatments reduced USK significantly as compared to the control (clean orchard understory) and that treatment 2 (trap crop + alley grass) was also significantly better at controlling stinkbugs than treatment 1 (alley grass). These results did not include the damage to nut kernel caused by the two-spotted stinkbug (*Bathycoelia natalicola*) as this species is highly monophagous and was not attracted to the trap crops although the increased plant diversity created by the treatments probably also contributed to lower levels USK for this species, because of both the *natural enemies' hypothesis* (more predators present) and the *resource concentration hypothesis* (having more trouble locating the host species) (Root, 1973). Hypothetically, the overall improved (lower) USK which was achieved with the treatments may not have been good enough to exclude the total use of chemical pesticides but has demonstrated the potential to significantly reduce the use of these chemicals and more especially proved that total organic conversions are achievable with macadamias.

5.2.1.1 Economic Considerations

Figure 22 summarizes the reduction in USK for these trials, which resulted in an overall reduction from 6.6 % USK in the control to 2.3 % USK in the combined treatment (trap crop + alley grass). From an ecological sustainability point of view, an USK of 2.3 % is an acceptable level, still yielding profitable returns. Commercial considerations which prioritize profit margins however, would still opt to include some chemical control to reduce USK to below 1 %. Macadamia nuts are highly profitable and small increases in USK consequently represent significant losses in profit.

Typically, a 1 % increase in USK could result in a loss of income of more than R1500.00 per ton nut kernel or R2000.00 per hectare (at current prices and exchange rates at an average total kernel yield of 30 %). Many variables however affect the price obtained, but as an example; a medium size hypothetical macadamia farm in South Africa yielding about 30 tons kernel per annum could equate to a loss in income of more than R50 000.00 for each percentage increase in USK for the season's crop. Conversely, pesticide spraying could easily cost more than R1500.00 per hectare (depending on the product used) which could add up to more than R30 000.00 per spray for the farm size mentioned above (25 hectares of orchards) yielding about 30 tons of kernel per annum. The use of the full treatment (trap crops + alley grass) reduced USK with 4.3 % in these trials, which would have resulted in an additional income of R215 000.00 to the hypothetical farm above, as compared to the 6.6 % USK of the control in the trials.

Without the trap crop treatments, commercial practises would typically have done 5 – 6 pesticide sprays per season, reducing the USK to 1 % from the 6.6 % in the trial controls. This would have related to an additional income of R280 000.00 for the hypothetical farm. The 5 – 6 pesticides sprays could however cost as much as R150 000.00 – R180 000.00, reducing the profit to R120 000.00 - R100 000.00 whereas the trap crop + alley grass treatment without spraying would have yielded and additional estimated R215 000.00 in income for the hypothetical farm (yielding 30 tons of kernel per season). Cultivating the trap crops in this case would have cost an estimated R25 000.00 for the hypothetical farm which would still have resulted in an estimated profit of R190 000.00 with an USK of 2.3 % as compared to the potential R120 000.00 if the same farm had been sprayed 5 times with a pesticide and achieved a 1% USK.

5.2.2 Soil Quality Trials

Considering the issue of soil quality maintenance and restoration, trials had to be modified according to local circumstances in macadamia orchards and, although cover crops may have affected significant changes in the soil where they were cultivated (in the tree alleys), they played a secondary role in the target root zone areas, mainly contributing organic material for composting purposes which was then applied as a mulch under the trees. In summary it was clear that although not all the soil quality indicators that were employed to assess changes in the soil with compost treatments improved significantly, a holistic consideration of all indicators, however, portrays an overall improvement which was particularly significant in the degraded soil plots where the topsoil had been removed by prior agricultural activities. From the chemical indicators used for the study, the cation ratios improved significantly in general. The negative changes that did take place of P, pH and some trace elements have been discussed extensively in chapter 4 and as was pointed out, may have resulted in positive values if the compost did not contain high levels of dairy manure. This, however, produced a valuable lesson about the danger of utilizing animal manure in this fashion without first analysing its chemical contents. The notable exceptions where chemical indicators did not improve were Na which increased too high as a side-effect of the mineral content of the dairy manure used in the compost and the Cu which decreased temporarily (Cu negative period) as was explained in chapter 4.

Two of the physical soil quality indicators improved significantly in the degraded trial plots only (available water content and soil penetrability) and the other two (bulk density and soil aggregate stability) which were analysed, did not show any significant changes. This is not necessarily a negative result, as physical changes in the soil are known to change slowly and the anticipated time needed for these changes to occur (16 months; time from first compost treatment to soil sampling), was probably under-estimated. None of the physical indicators, however, changed for the worse from a soil quality point of view.

Except for a springtail assessment which yielded no results, almost all the other biological indicators improved significantly in either the healthy or the degraded plots. No negative changes were observed in any of these trial plots after the compost treatments. Nematode analyses may be singled out in this category as it resulted in an intensive analysis which was able to portray improved soil conditions because of compost treatments.

5.2.2.1 Economic Considerations

Cost implications for cultivating cover crops depend on the level and mode of application, full surface area coverage (grain crop fields) with a crop like sunnhemp could cost as much as R2000.00 per hectare. Orchard applications however, are much cheaper as no tillage is done (zero tillage planting is used) and the available surface area for planting cover crops in an evergreen macadamia orchard is limited to about 50 % of the total orchard surface area which can be cultivated in the alleys and around the orchard borders. This brings the cost down to less than 30 % of the conventional crop field cost which would be less than R800.00 per hectare. When all that is gained is calculated however, the investment to plant cover crops becomes small in relation to the yield on investment, with the bonus of advancing towards ecological sustainability on top of direct financial gains. Savings in less fertilizer, healthier plants and soil, and optimal crop yields cannot however always be quantified financially, which often results in farmers rather following the road well tread which may no longer be relevant when sustainability becomes the priority.

5.3 Recommendations

5.3.1 Trap Crop Utilization

The use of sunnhemp as a trap crop is not without challenges of its own. The following lessons were learned from the study and may serve as useful guidelines to apply for the successful use of sunnhemp as trap crop for the green stinkbug species (*Nezara*) in macadamia orchards:

i) Stinkbugs are only attracted to the flowers and pods of these plants; hence the timing of cultivation is crucial. This poses a challenge as these crops take up to eight weeks to produce flowers and pods after germination, which means that it must be planted in mid-winter in South Africa to produce its first flowers and pods to coincide with the fruit set of the nuts in spring when they are most vulnerable to stinkbug damage. Sunnhemp is poorly adapted to growing in winter and cold weather and farmers must be innovative to be able to cultivate these plants in winter. One solution is greenhouse cultivation in plant bags where they are protected against cold temperatures. This is unfortunately cumbersome and can be costly but could provide the desired results. Another option is to protect individual plants in the orchards against the cold with the aid of grass mulching or even cardboard structures.

ii) Sunnhemp performed significantly better than the control plots in the presence of enhanced orchard plant diversity. The combination of providing alternative and more attractive host plants to the stinkbugs as well as enhancing orchard habitat for natural enemies proved to produce the best results. Natural orchard floor and edge vegetation also provide alternative food sources for the polyphagous stinkbug species and act as barriers between stinkbugs and macadamia trees. Allowing tree alley grass to grow in every alternate row and mowing the rest proved to be sufficient biodiversity enhancement for this purpose. When the plants (predominantly grass plants) in the alleys reach maturity and have flowered and cast their seed, these alleys can be mowed, and the alternate ones allowed to grow. A system which would allow the grazing of these alternate alleys in a concentrated fashion with large stock to graze off all the grass in the shortest possible period will greatly benefit the alley ecosystem. Even though the alley floor is disturbed. This may be repeated alternately in alley rows and allows for orchard management activities to proceed by using the open mowed alleys only.

iii) Trap crops should be cultivated in permanent enclosures around the perimeters of macadamia orchards at a rate of about a 30-meter strip of trap crop for every 200 meters of orchard perimeter distance. Enclosures should be permanent and designed to facilitate easy cultivation and access but sturdy enough to exclude small antelope like bushbuck, duiker and porcupine which tend to destroy these trap crops if it is not well protected.

iv) Trap crops should also be cultivated under irrigation but not linked to existing irrigation systems for macadamia crops if the fertilizers are applied through the irrigation system. Experience has shown sunnhemp to be too sensitive for the concentrations of soluble fertilizer products which may be provided to macadamia trees in conventional cultivation systems.

v) Sunnhemp should be stagger-cultivated to ensure the availability of flowers and pods for the full growing season as stinkbugs can damage macadamia nuts until they are harvested, despite the hard shell.

vi) Trap crops may be treated with a systemic insecticide like Imidacloprid which would then kill all stinkbugs feeding on the trap crops and prevent possible breeding on the trap crops.

vii) Sunnhemp does do not provide a blanket protection against the green stinkbugs and farmers should scout regularly to determine the status of stinkbug populations in their orchards.

Although all the *Nezara* species are attracted to sunnhemp (these species are all polyphagous), the two-spotted stinkbug (*Bathycoelia natalicola*) is not attracted to any known trap crop as it is strongly monophagous. Two-spotted stinkbugs, endemic in southern Africa, pose a significant threat to macadamia crops. This species has adapted extremely well to macadamia crops and it flourishes within macadamia orchards. Apparently, all its habitat requirements are met in this environment and from here it disperses slowly. Much research needs to be done to find solutions for this species as trap crops do not attract it. Natural predator enhancement and strategies such as the use of semiochemicals currently present the highest potential for managing this pest sustainably.

5.3.2 Soil Quality Management

Jenkins (2004) recommended general applications of 0.5 – 2 m^3 of compost per tree (16 – 20 m^2) as a soil mulch in macadamia orchards. The trials of this research project demonstrated that 0.5m^3 per tree (16m^2 root zone area) was enough to maintain a healthy soil, as was found in the study area, and that 1m^3 per 16m^2 root zone improved degraded soils significantly. Experience taught that although sunnhemp provides large quantities of plant biomass which may be composted, the amount needed for successful trap cropping does not yield enough biomass to provide enough amounts of compost for the applications as recommended above. Other sources of organic material should therefore be used to supplement the available sunnhemp biomass, which may be mowed for composting as soon as the macadamia crop is harvested. These include any supplies of suitable composting materials, preferably on site, such as dry grass, macadamia husks, wood chips and animal manure. As discussed in chapter 4, caution should, however, be used when animal manure is used.

5.4 Closing Statement

We have yet much to learn and the progress is slow, but this research has demonstrated the potential to convert conventional macadamia farming which is currently practised world-wide as a monoculture, to more sustainable agroecosystems. The sooner we learn to view these orchards and farms as ecosystems, the sooner we may learn how to redesign and manage them sustainably. In the context of a macadamia orchard, such an ecosystem will involve related weed plants, natural host plants as well as arthropod complexes, combined with strategies like the addition of trap crops, bat houses and other cultural devices (like cultivar choice), with the aim of creating unfavourable conditions for pests, but at the same time rendering growing conditions for the cultivation of the crop plant as optimal as possible by optimizing soil health.

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