SOIL FERTILTIY ENHANCEMENT THROUGH APPROPRIATE FERTILIZER MANAGEMENT ON WINTER COVER CROPS IN A CONSERVATION AGRICULTURE SYSTEM

By

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DECLARATION

I, Ernest Dube, declare that the content of this thesis is entirely my own work with the exception of such quotations or references which have been attributed to their authors or sources. I also declare that all photographs are made or drawn by me except where I have acknowledged another as the author. This thesis has not been previously submitted to this or any other university for a degree.

Signed at Alice this ………day of …………………..2012

…………………………

Ernest Dube

PREFACE

This thesis is made up of eight chapters. Chapters 1 and 2 (general introduction and literature review) introduce the reader to soil fertility problems on smallholder farmlands in the Eastern Cape Province, including a review of soil fertility improvement through oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) winter cover crops in conservation agriculture. This is followed by Chapter 3, which examines the effects of the winter cover crops and fertilizer on soil organic matter. Chapter 4 deals with the effects of winter cover crops and fertilizer on phosphorus pools. Chapter 5 looks at the effects of the winter cover crops and fertilizer on nutrient availability, maize yield and nutrient uptake. The next chapter (Chapter 6) focuses on the effects of winter cover crops on nitrogen management, agronomic efficiency and profitability. In Chapter 7, the effects of the winter cover crops and fertilizer on soil seed banks of problematic weeds are reported. Finally, general discussion, conclusions and recommendations are reported in Chapter 8.

ABSTRACT

A study was carried out to determine the effects of oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) winter cover crops and fertilizer application on SOM, phosphorus (P) pools, nutrient availability, nutrient uptake, maize yield and seedbanks of problematic weeds in an irrigated maize-based conservation agriculture (CA) system. A separate experiment was carried out to investigate the effects of the winter cover crops on nitrogen (N) management, N use efficiency and profitability.

After four years of continuous rotation, the winter cover crops significantly ($p<0.05$) increased particulate SOM and hot water soluble carbon in the 0 – 5 and 5 – 20 cm soil depths. When fertilized, oat was better able to support SOM sequestration in water stable aggregates at 0 – 20 cm whilst grazing vetch was more effective at 20 – 50 cm. Where no fertilizer was invested, there were significant ($p<0.01$) reductions in biomass input and SOM on oat-maize and weedy fallow-maize rotations whereas vetch-maize rotations did not respond, both at 0 – 5 and 5 – 20 cm. Targeting fertilizer to the winter cover crop required less fertilizer, and yet gave a similar SOM response as targeting the fertilizer to the maize crop. In addition to increasing SOM in the surface soil (0 – 5 cm), the winter cover crops significantly ($p<0.05$) increased labile pools of P, including microbial P. The cover crops also significantly ($p<0.05$) increased maize P concentration during early growth, extractable soil P, Cu, Mn, and Zn but had no effect on Ca and K. Grazing vetch increased soil mineral N but reduced extractable soil Mg. Without fertilizer, there were sharp declines in maize grain yield on oat and weedy fallow rotations over the four year period, but less so, on the grazing vetch.

Grazing vetch increased maize growth, grain yield response to N fertilizer, nitrogen use efficiency (NUE) and profitability for fertilizer rates below 180 kg N ha^{-1}. Oat effects however on maize yield and NUE were generally similar to weedy fallow. Based on the partial factor productivity of N, the highest efficiencies in utilization of fertilizer N for maize yield improvement under grazing vetch and oat are obtained at 60 kg N ha^{-1} and would decline thereafter with any increases in fertilizer application rate.

Grazing vetch gave N fertilizer replacement values of up to 120 kg N ha^{-1} as well as the highest marginal rates of return to increasing N fertilizer rate. The cover crops were more effective than the weedy fallow in reducing seedbank density of *Digitaria sanguinalis*, *Eleusine indica*, *Amaranthus retroflexus* and *Datura stramonium* at 0 – 5 cm soil depth, causing weed seed reductions of 30 - 70%. The winter cover crops however, selectively allowed emergence of the narrow leafed weeds; *Cyperus esculentus* and *Digitaria sanguinalis* in the maize crop.

The findings of this study suggested that grazing vetch is suited for SOM improvement in low fertilizer input systems and that fertilizer is better invested on winter cover crops as opposed to maize crops. Oat, on the other hand, when fertilized, would be ideal for C sequestration in water stable aggregates of the surface soil. Grazing vetch is ideal for resource poor farmers who cannot afford mineral fertilizers as it gives grain yield improvement and high fertilizer replacement value. Grazing vetch can produce enough maize yield response to pay its way in the maize-based systems and oat may not require additional N than that applied to the weedy fallow. Phosphorus and Zn are some of the major limiting essential plant nutrients on South African soils and the winter cover crops could make a contribution. The cover crops also hasten depletion of some problematic weeds from seedbanks, leading to reduced weed pressure during maize growth.

Keywords: Fertilizer; grazing vetch; maize yield; nitrogen; nutrient availability; oat; phosphorus; soil organic matter

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1 GENERAL INTRODUCTION

1.1 INTRODUCTION

Soils in many areas of the Eastern Cape (EC) province of South Africa where smallholder farming is practiced are prone to erosion and rapid degradation due to high sand and silt contents, and profile morphologies that have clay accumulation in the subsoil, particularly on soils developed from mudstones and shales (Mandiringana *et al.,* 2005). Medium textured young soils, usually of shale and sandstone predominate on many of the smallholder farmlands in the EC (Laker, 1978). A South African national state of the environment report (Hoffman *et al.,* 1999) identified the EC province as having the second highest level of land degradation. Lack of ground cover, overgrazing, intensive tillage, short-to-no fallow periods and limited crop rotation were identified as causes of the degradation, which reduce inherent soil fertility among other effects.

In a survey covering 31 magisterial districts of the EC where smallholder farming is practiced, Mandiringana *et al.* (2005) found that most soils were low in soil organic matter (SOM) (<1%) and deficient in nitrogen (N), phosphorus (P) and zinc (Zn). This poor soil fertility situation is exacerbated by maize monoculture and continuous cropping, which results in vast removal of nutrients with practically nothing being returned to the soil in the form of manures or fertilizers (Bembridge, 1984). Mei *et al.,* (1995) found poor inherent soil fertility to be one of the reasons for abandoning of crop production in the EC by smallholder farmers. Similarly, Maqubela (1999) reported critically low plant available P concentrations (0.6 – 6.1 ppm) in some soils of the central region of the EC.

Farming practices that encourage accumulation of SOM as well as prevent soil erosion are needed to be adopted in the region for ameliorating soil fertility problems.

In most parts of the world, chemical fertilizers play a major role in maintaining or increasing soil fertility and maize yield. However, such is not generally the case in smallholder systems of the EC, where the majority of farmers are resource poor. For example, Bembridge (1987) reported that only 31% of the smallholder irrigation farmers in the EC used fertilizers for growing maize, and the fertilizers may be applied once in every three years (Monde *et al.,* 2005). Some of the farmers use low quantities of inorganic fertilizer (<60 kg N ha^{-1}) against the recommended rates (200 kg ha^{-1}) on maize (Fanadzo *et al.*, 2010).

Conservation agriculture (CA) is increasingly gaining acceptance across the world as an alternative farming approach for sustainable soil fertility improvement (FAO, 2008). It is defined as a concept for resource saving agricultural crop production that strives to achieve acceptable profits along with high and sustained production levels while concurrently conserving the environment (FAO, 2008). The three principles of CA are minimal mechanical soil disturbance, permanent organic soil cover through cover crops and diversified crop rotations. For CA to be successful, the principles have to be applied correctly, holistically and simultaneously (Bollinger *et al.*, 2007). The principles are applicable to a wide range of crop production systems, from low-yielding rain-fed conditions to high yielding irrigated conditions (Verhulst *et al.*, 2010). The potential of CA to increase soil fertility and crop yield is site specific and depends mainly on the local bio-physical and socio-economic environment (Erenstein, 2003; Giller *et al.*, 2009). The

CA technology can however be tailor made through research and innovation so that it suits the targeted farmers in their environments.

Efforts have been made to promote CA in smallholder systems of South Africa and success was limited in terms of uptake of the technology. For example, the South African Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW) introduced CA principles of mininimal mechanical soil disturbance and crop residue soil cover based on Latin American experiences to some smallholder maize farmers of the EC, Mpumalanga and KwaZulu Natal to try and solve soil fertility and acidity problems, but there was virtually no uptake of the technology (Fowler, 1999). Conservation agriculture benefits reported elsewhere such as improved soil fertility, soil conservation, reduced weed pressure and increased income were not observed in the systems. The Massive Food Production Program (MFPP), a brain child of the Eastern Cape Department of Agriculture and Rural Development, was another project which embraced CA principles based on Brazilian experiences to address maize production challenges in smallholder farming areas of the EC. Likewise, this CA promotion effort did not make a significant impact (Bollinger *et al.*, 2006).

Adequate and permanent crop residue cover has been identified as a key missing element which resulted in failure of CA practice to provide any substantial benefits in smallholder systems of South Africa (Derpsch, 2005). The use of cover crops is an important strategy to achieve permanent soil cover and generate high amounts of crop residues in CA systems. Cover crops are defined as crops grown specifically for covering the ground to protect the soil from erosion and loss of plant nutrients during the season of the year when main crops do not occupy the land (Clark, 2007). In warm temperate regions such as the EC where maize is the main summer crop, cover crops can be grown over the winter, provided irrigation water is available. Upon termination of the winter cover crops, nutrients are returned to the soil and a quantity of organic matter is added. Winter cover crops absorb nutrients from the soil which otherwise would be lost to leaching and in the case of legumes, considerable amounts of N may be added to the soil.

Maximum potential maize yields are compromised by mono-cropping and annual depressions in grain yield can range from 5 – 15 % of maximum potential yield (Erickson & DeBoer, 2004; Natziger *et al.*, 2005). Winter cover crops bring an element of crop rotation into maize-based systems which could result in yield increase, through a number of factors such as breaking of pest and disease cycles, more efficient weed control and improved nutrient cycling. These advantages of winter cover crops are common to both grass and leguminous species. Where differences in effects between these winter cover crop types occur, they are mostly related to N-fixation by legumes and resultant differences in N content of residues between the two groups. Grass species may immobilize N over a short period due to their wide C:N ratio, but they generally provide higher biomass yield and better cover against soil erosion than legumes (Clark, 2007). Proper N fertilizer management following both leguminous and grass winter cover crop species is important for optimizing grain yield and maximizing profitability, as well as minimizing environmental contamination.

An appropriate winter cover crop for a maize-based cropping system, whether grass or legume should; i) be easy to establish and adapted to the environment; ii) have a rapid growth rate so as to provide ground coverage quickly; iii) be economically viable; iv) be disease resistant and not act as a host for maize diseases; v) be easy to kill and most importantly; vi) produce a sufficient quantity of biomass. Research has been carried out to evaluate appropriate winter cover crop species and fertilizer management for increasing biomass input in irrigated maize-based CA systems in the EC (Murungu (2010). Grazing vetch (*Vicia daryscapa*) and oat (*Avena sativa*) are the most promising winter cover crops among those that have been tested in this regard. Where residual fertilizer in soils is limited, winter cover crop biomass yield might be limited, and fertilizer application to the winter cover crops can increase biomass production. The use of fertilizer on winter cover crops may not necessarily represent inefficient fertilizer usage since the cover crops would return the nutrients to the soil upon their termination. It is envisaged that high biomass yielding oat and grazing vetch winter cover crops will improve soil fertility on smallholder farms in the EC. Scientific evidence however, is required regarding this matter. The aim of this study was to quantify the effects of oat, grazing vetch winter cover crops and fertilizer management on soil fertility and maize yield.

Apart from poor soil fertility, weeds are a major problem causing low maize yields in smallholder farmlands of the EC. In the absence of good weed management, the benefits of improved soil fertility may not be realized and it is therefore important to evaluate the effects of crop management systems on soil fertility and weed management concurrently. Organic mulch derived from winter cover crops can decrease weed emergence as well as enhance weed seed loss mechanisms (Baldoni *et al.*, 1999; Davis *et al.*, 2005). It was therefore necessary to extend this study to look at winter cover crop effects on soil weed-seedbanks and weed pressure under continuous practice of CA.

1.2 STUDY HYPOTHESES AND OBJECTIVES

The hypothesis for this study was:

(i) Oat and grazing vetch winter cover crops and appropriate fertilizer management on both winter cover crops and the maize crop can enhance soil fertility through improving SOM and essential mineral nutrients, resulting in increased maize yield, profitability and reduced weed pressure.

To test this hypothesis, the study was undertaken with the following objectives:

(i) To determine the effects of the winter cover crops and fertilizer management on SOM

(ii) To determine the effects of the winter cover crops and fertilizer on nutrient availability, nutrient uptake and maize yield

(iii) To determine the effects of winter cover crops and fertilizer application on soil phosphorus pools

(iv) To determine the effects of the winter cover crops on N management, N use efficiency and profitability of maize

(v) To determine the effects of winter cover crops and fertilizer application on soil weed seedbanks and weed emergence under continuous practice of CA

2 LITERATURE REVIEW

2.1 BACKGROUND

Covering an area of 169 580 km^2, the Eastern Cape (EC), which is the second largest province of South Africa, is composed of a high rural population (69%) (Statistics South Africa, 2003). Fertile soils are limited in the EC, thus making the majority of the population to settle on medium textured and shallow soils in low rainfall areas (DEAT, 2003). Smallholder farmer irrigation schemes have been established in attempts to improve maize production and living standards for rural people in the EC (Bembridge, 2000). Examples of these include Zanyokwe (439 ha), Tyefu (641 ha), Keiskammahoek (744 ha), Shiloh (455 ha), Qamata (1959 ha) and Ncora (2490 ha). These schemes are subdivided into plots averaging 4 ha that are managed independently by the farmers. Despite the introduction of irrigation, maize grain yields remain low (<3 Mg ha^{-1}) among the resource poor smallholder irrigators, mainly due to soil fertility problems. Conservation agriculture (CA) is widely viewed as a possible sustainable solution to soil fertility problems in smallholder farmlands of the EC.

High biomass yielding cover crops are a key component for the success of CA as it plays an important role in soil conservation, maintaining soil organic matter (SOM) and improving soil nutrients. To achieve this, the inclusion of oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) winter cover crops in maize-based systems could be an important strategy. This literature review explores from a global perspective, the prospects and opportunities for soil fertility and maize yield improvement through inclusion of oat and grazing vetch winter cover crops in maize-based systems. In addition, the review helped to indentify information gaps that have shaped specific objectives for this research as reported in subsequent chapters.

2.2 SOIL FERTILTIY AND SOIL DEGRADATION IN THE EASTERN CAPE

The definition of soil fertility varies among researchers (e.g. Larson & Pierce, 1991; Charman & Murphy, 2000; Brady & Weil, 2008). At the onset of this review, it therefore becomes pertinent to define the term 'soil fertility'. From an agronomic perspective, soil fertility can be defined as a measure of the soil's ability to sustain satisfactory crop growth, both in the short- and longer-term, and it is determined by a set of interactions between the soil's physical environment, chemical environment and biological activity. Soil fertility is not a distinct property of the soil and consequently, there is no consensus on the definition of soil fertility, as well as a method for measuring soil fertility. The fertility of a soil is therefore a subjective notion and is defined in relation to people's interests. Although this review acknowledges the role of physical and biological fertility attributes, it will focus primarily on some chemical aspects of soil fertility that are important to maize growth and considered to be an expression of all contributing factors, whether biological, chemical or physical.

The EC is one of three most soil-degraded provinces in South Africa (Hoffman *et al.,* 1999). As is evident from Plate 2.1, almost half of the EC province is moderate to severely degraded. Monoculture cereal production, intensive tillage, short-to-no fallow periods and inappropriate land use are suspected to be some causes of the degradation.

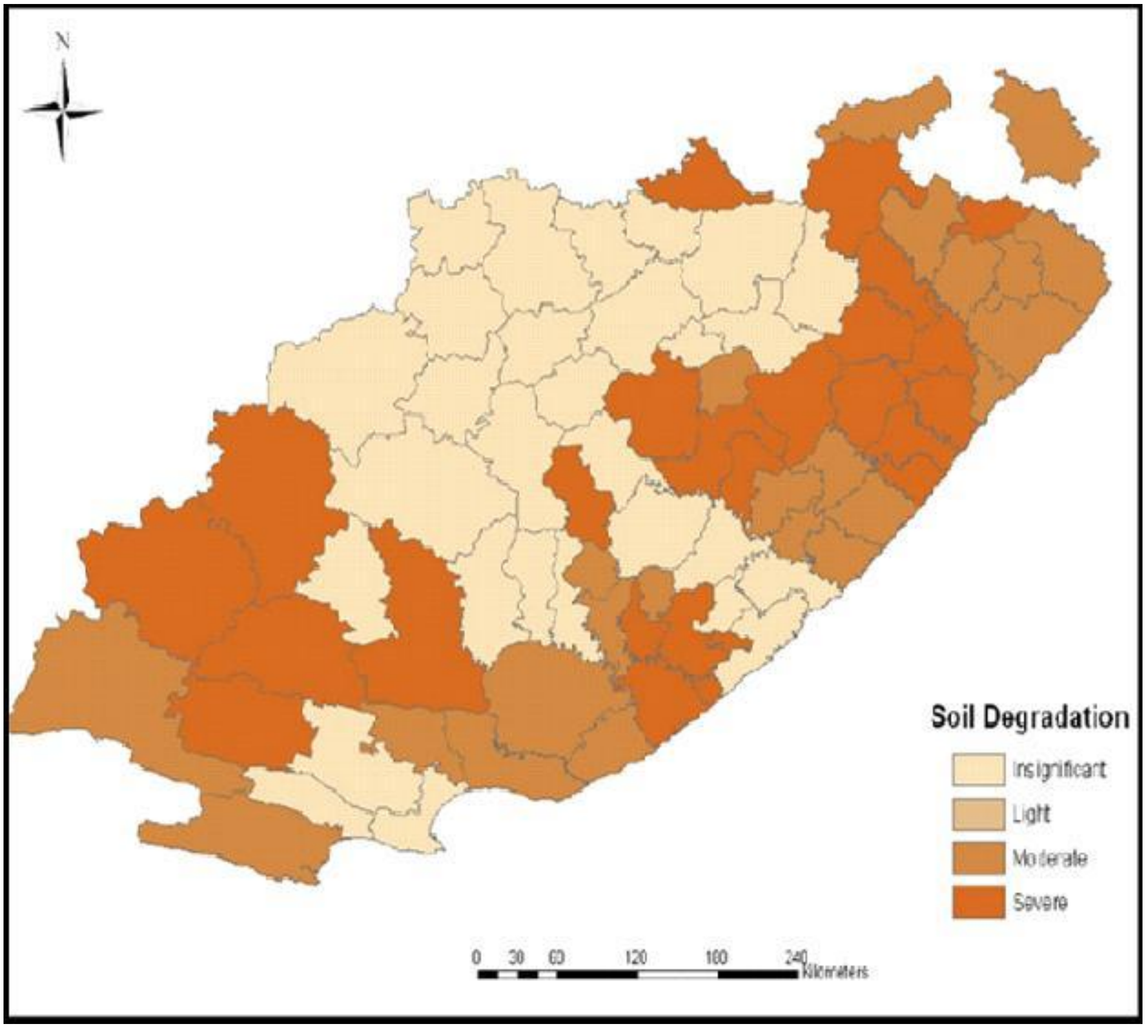


Plate 2.1 Map depicting the extend of soil degradation in the Eastern Cape Province (Hoffman *et al.*, 1999)

According to Hoffman & Ashwell (2001), eight of the twenty districts requiring priority attention in terms of land degradation in South Africa are found in the EC. The districts include Herschel, Qumbu, Mount Fletcher, Engcobo and Middledrift. These areas are also faced with a worsening problem of soil fertility decline and low yields (Mandiringana *et al.,* 2005). According to Hoffoman *et al.* (1999), degraded areas in the

Eastern Cape (Plate 2.1) closely correlate with the degraded areas presented on the land cover maps of the EC.

Under dry-land conditions, average maize yields in smallholder farmlands of the EC declined from around 700 kg ha^{-1} in the 1930's down to 200 kg ha^{-1} in the 1980's due to soil degradation and soil fertility decline (Bembridge, 1984). It was also estimated that the area of land used for crops and grazing decreased slightly during the period 1988–98 and land degradation was partly responsible for this, among other factors such as drought, increased production costs, lack of support for communal farmers and the collapse of agricultural infrastructure (Hoffman *et al.*, 1999). In a soil fertility survey covering soils of 31 magisterial districts in the EC where most smallholder irrigation agriculture is practiced, Mandiringana *et al.* (2005) found the soils to be generally low to very low in their available nutrients. This effect was ascribed to low SOM levels and low geological reserves of some nutrients notably P, K and Ca, coupled with continuous maize monoculture without adequate nutrient replenishment.

2.3 THE IMPORTANCE OF SOIL ORGANIC MATTER TO SOIL FERTILITY

Whilst there is no consensus on the definition of, or measure of soil fertility, there is no disagreement in the current literature about the proposition that organic matter content gives soils their desirable properties in terms of fertility (Charman & Murphy, 2000; Brady & Weil, 2008). Soil organic matter is at the center of nutrient cycling as it acts as a nutrient store-house, increases the cation exchange sites and supports soil biological activity (Brady & Weil, 2008). Its cation exchange can contribute between 20 – 70% of the total cation exchange capacity of low clay soils (Brady & Weil, 2008). Soil organic matter also improves the water holding capacity of soils (Allison, 1973; Saxtona & Rawls, 2005).

Soil organic matter can be subdivided into pools in order to identify small changes occurring in total SOM that are difficult to detect because of the generally high background levels and natural soil variability (Blair *et al.,* 1995; Haile-Mariama *et al.,* 2007). The active fraction contains plant, animal, and microbial residues that are decomposing and it is a source of many essential plant micronutrients (Loveland & Webb, 2003). Particulate organic matter and hot water soluble organic matter are some important pools of the active fraction (Swift & Woomer, 1993; Körschens *et al.,* 1998). The living fraction contains living soil biota or biomass made up of microorganisms and plant roots whilst the recalcitrant or passive fraction contains organic matter that is chemically and physically resistant to biodegradation (Schloter *et al.,* 2006). Humified organic matter regulates different aspects of soil quality which includes the outcome of ionic and non-ionic compounds, soil cation exchange capacity and the permanent stability of micro-aggregates (Herrick & Wander, 1997).

2.4 APPROACHES THAT HAVE BEEEN USED TO IMPROVE SOIL ORGANIC MATTER IN SMALLHOLDER SYSTEMS OF SA

Fertilizers can be used to enhance crop yield, biomass input and therefore organic matter additions for SOM improvement. In South Africa, N and P are some of the most limiting nutrients to crop production and inorganic fertilizers prescribed for ameliorating N and P deficiencies include super phosphate, urea, lime of ammonium nitrate (LAN), mono-ammonium phosphate (MAP), di- ammonium phosphate, (DAP) and NPK compound fertilizers. Most of the fertilizers are fortified with 0.5 % zinc. Nitrogen fertilizer production in SA does not meet demand (Table 2.1) and N fertilizer prices have increased beyond the reach of many smallholder farmers.

Table 2.1 Nitrogen fertilizer production in South Africa

	Demand	Domestic Production	Imports
Quantity (Mg)	400 000	250 000	150 000
Products	All forms	Mostly CAN, some AS	Mostly urea, some CAN and AS

Source: Machete *et al*., 2004

It has often been suggested by researchers that agronomical research in the EC may need to focus on alternative sources of nutrients to inorganic fertilizers for soil fertility improvement (Mandiringana *et al.*, 2005; Fanadzo *et al.*, 2010). Alternatives for improving soil fertility in the smallholder farming communities of the EC include application of cattle manure (Mkile, 2001), human urine (Mnkeni *et al.*, 2005), goat manure (Gichangi, 2008), cyanobacteria (Maqubela *et al.*, 2010) and composts (Mupondi *et al.,* 2010). More recently, the search for sustainable solutions to soil fertility challenges has focused on conservation agriculture (CA). The major principles of CA are minimum soil disturbance, crop rotation and permanent soil cover through cover crops.

Conventional farming practices based on extensive tillage and mono-cropping, especially when combined with removal or in *situ* burning of crop residues magnify soil erosion losses, land degradation and soil fertility challenges experienced by the farmers. The aim of CA is to create economically and environmentally sustainable agricultural production, with the emphasis placed on self-sustaining systems, rather than external inputs (FAO, 2008). The benefits from CA practice can include reduced pest and disease problems, water and wind erosion, reduced runoff and enhanced SOM, which is associated with long term sustainable productivity. Experience gained from Brazil and many other parts of the world show that CA is a crop production practice which can be used to enhance soil fertility, SOM and crop yields (Bollinger *et al.,* 2006). However, whether these benefits can be realized on smallholder farms in Sub-Saharan Africa has been a subject of debate (Giller *et al.*, 2009).

2.5 EFFORTS TO PROMOTE CONSERVATION AGRICULUTRE IN SMALLHOLDER SYSTEMS OF SOUTH AFRICA

The concept of CA is not entirely new to smallholder systems of South Africa. In the 1970's researchers tried to promote minimal tillage as an entry point to CA in various provinces to address increasing land degradation problems but with limited success (Fowler, 1999). Farmers ran into serious weed, pest and disease as well as nutrient management problems.One of the missing elements found in the reduced tillage system was identified as permanent and adequate soil cover (Fowler, 1999). More recently (2002), the South African Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW) introduced CA principles based on Latin American successes to smallholder farmers of Mpumalanga, KwaZulu Natal and the EC to try and solve soil fertility and acidity problems, but with limited success in terms of uptake of the technology. The Massive Food Production Program (MFPP), a brain child of the Eastern Cape Department of Agriculture and Rural Development (ECDARD), was another project which embraced CA principles to address crop production challenges in smallholder farming areas of the EC, again with limited success. According to Bollinger *et al.* (2006), efforts towards CA in SA have not made significant impact at the smallholder farmer level. The Conservation Agriculture Thrust (CAT) was formed in 2007 as a joint initiative between the ECDARD and the University of Fort Hare (UFH) with the aim of promoting CA in the EC through training and exposing extension officers, their supervisors and farmers to CA by conducting demonstration trials. The objective of CAT is to have the majority of farmers in the EC embracing and practicing CA by 2012.

Successful CA is achieved through community driven development processes whereby local researchers, communities and farmer associations identify and implement the best options for CA in their locations (Dumanski *et al.* 2006). The potential of CA as a soil conserving technology is site specific and depends on the local bio-physical and socio-economic environment (Erenstein, 2003). Whilst ongoing CA efforts in the EC such as the CAT would require a back up of scientific information in order to carry out informed farmer training and extension on best management practices for CA in smallholder systems of the EC, limited scientific research has been carried out towards tailor-making CA to address soil fertility challenges faced by the farmers.

In Latin America, research and innovation into strategies for maintaining permanent soil cover with a thick layer of biomass as mulch was one of the key factors for success of CA (Bollinger *et al.,* 2006). High amounts (6 Mg ha^{-1} or more) of permanent biomass derived from cover crops minimized soil erosion, provided good weed suppression, and improved SOM and soil fertility towards reduced weeding and fertilizer costs. Similarly, research and innovation into strategies for increasing biomass and SOM in low input smallholder systems of South Africa could be the key to success. It is noted that the need to protect the land from erosion and degradation may not be adequate enough motivation for resource poor smallholder farmers to invest in CA. Other observable and more immediate benefits, such as soil fertility improvement and concomitant reductions in fertilizer requirements for maize production may persuade farmers to adopt CA. An inability of CA technologies to demonstrate clear results and economic advantage to the target users is cited as one of the reasons behind poor and slow uptake of CA in smallholder systems of SA (Derpsch, 2005).

2.6 HOW MUCH SOM IS REQUIRED FOR SOIL FERTILITY?

Although SOM is central to sustaining soil fertility, there have been attempts to establish threshold values for SOM, below or above which its beneficial effect is diminished. Howard & Howard, (1990) estimated that the lower threshold was 2% soil organic carbon (SOC), below which soils with low clayare prone to structural destabilization and crop yield reduction. Soil organic carbon levels on many smallholder farmlands in the EC fall below 1%. Kay & Angers (1999) asserted that if SOC contents are below 1%, it may not be possible to obtain potential yields irrespective of soil type. Even though it is not easy to increase the SOM content of soils, small increases as little as 0.5% can significantly improve soil fertility (Brady & Weil, 2008).

Conversely however, Haynes & Naidu, (1998) suggested that 'too much' SOM can result in surface crusting, increased detachment by raindrops and decreased hydraulic conductivity if organic wastes used in the SOM formation are high in monovalent cations. No clear indication, however, exists in the literature on exactly how much SOM is excess, or enough for the fertility of a soil. Soil organic matter is important to soil fertility as it is decayed to form humus. A soil is more productive as more organic matter is regularly decomposed and its simpler constituents (nutrients) made usable during the growing season. The mere presence of SOM in the soil (regardless of how much) is of value when it influences soil structure, cation exchange capacity and water storage. The objective of good SOM management in low fertilizer input smallholder systems, as found in the EC, would therefore be to have a steady supply of easily decomposable SOM to supply maize with nutrients during the growing season.

Continuous addition of increased amounts of organic materials does not result in continuous increase in SOM. The ability of a soil to stabilize C is largely determined by climate, soil texture and soil mineralogy, with other soil parameters such as water-holding capacity, pH, and porosity acting as rate modifiers (Six *et al.*, 2002). Clay and humified organic matter tend to be closely associated in the soil, which reduces the surface area available for attack by saprophytic organisms. Thus, with increasing organic matter inputs, fine-textured soils would hold higher SOM content at equilibrium than coarse-textured soils. In a 90 year field trial, Körschens *et al.* (1998) found that sandy soils containing 3% clay equilibrated at 0.7% SOC and soils with 21% clay reached 2.0% SOC. Based on this data, the authors proposed lower and upper limits of SOC for soils with different clay contents. For soils with 4% clay, the lower and upper limit of 1% and 1.5% was proposed and for soils with 38% clay, the respective limits were 3.5 and 4.4%. The average SOM content also increases two or three times for each drop of 10° C in annual temperature, provided the precipitation-evaporation ratio is kept constant (Brady & Weil., 2008). In tropical Brazil, on heavily weathered soils and with annual temperatures close to or above 20°, 8 – 10 Mg of residue dry mass ha^{-1} are needed per year in order to maintain the SOM stocks against depletion under zero-till (Bollinger *et al.,* 2007).

It appears that low clay contents in smallholder farms of the EC present a limitation for SOM restoration and maintenance. However, it should also be noted that lower average annual temperatures in warm temperate zones such as the EC would lessen decay and increase accumulation of SOM by carry-over from season to season. The adoption of no till can have a further effect of reducing SOM decomposition rate whilst winter cover crops would increase residue return.

In CA systems, organic matter accumulates on the surface due to the combination of mulch retention practices and no till. Stratification of organic matter brings into question the optimum sampling depth in terms of characterizing the SOM status under CA. Sampling depth for conventional row crops is normally 0 – 15 or 0 – 20 cm. Franzluebbers (2002) found that the accumulation of OM at the soil surface (0-5 cm) is of major importance in terms of the functioning of the soil ecosystem. Surface OM has profound effects on aggregate stability, water infiltration, aeration and nutrient cycling.

Since SOM is made up of thousands of organic compounds derived from different kinds of organic materials, it is measured through analytical methods that determine the SOC content and convert it to SOM using a conversion factor. Broadbent (1953) recommended the use of 1.9 and 2.5 factors to convert SOC to SOM for surface and subsurface soils, respectively. Schumacher (2002) argued that there can be no universal conversion factor as the factor varies from soil to soil, between soil horizons within the same soil, and is dependent upon the type of organic matter present in the sample. Regardless of this complexity, a conversion factor of 1.724 is generally used in many research studies to convert SOC to SOM, based on the assumption that organic matter contains at least 58% organic C (Nelson & Sommers, 1982).

2.7 SOIL FERTILITY BENEFITS FROM WINTER COVER CROPS

Cover crops are literally “crops that cover the soil” and may be used to reduce soil erosion, reduce N leaching, provide cover to suppress weed prolification as well as increase increase SOM. From this context, winter cover crops are planted shortly before or soon after harvest of the main grain crop and are terminated before or soon after planting of the next grain crop. Their residues are left on the soil surface to serve as mulch. Small grain winter cover crops such as oat, winter wheat, barley, triticale, and winter rye grow rapidly in cool weather and withstand moderate frost (Clark, 2007). Leguminous winter cover crops can fix N in low N soils; however, they usually don’t produce as much biomass as the small grains and their seed is relatively expensive.

Research has been carried out for evaluating appropriate winter cover crop species for irrigated maize-based CA systems in the EC (Murungu, 2010; Musunda, 2010). Grazing vetch (*Vicia darsycarpa*) and oat (*Avena sativa*) winter cover crops appeared as ideal candidates for this matter. Under irrigation, vetch and oat winter cover crops can produce biomass in excess of 6 Mg ha^{-1} dry weight annually while providing good permanent cover. The resource constrained smallholder farmers of the EC normally do not plant winter crops (Fanadzo, 2009). In this case, winter cover crops could be ideal for them as they would result in minimal disturbance of the farming system. Several soil fertility benefits that can be obtained from winter cover crops are discussed in the sections below.

2.7.1 Soil organic matter improvement

Winter cover crops supply organic matter to the soil through decomposition of their residues. Oat can produce up to 12 Mg ha^{-1} above-ground biomass (AGB) under optimal fertility conditions and this is greater than vetch which generally yields 3 - 6 Mg ha^{-1} (Hargrove *et al.,* 1986; Smith *et al.,* 1987). Root biomass is also an important source of SOM and it is estimated at 11% of AGB for vetch (Shipley *et al.*, 1992) and 17% of AGB for oat (Hoad *et al.*, 2001). There is evidence suggesting that SOM accumulates over time in no till systems, mostly in the top 5 cm of the soil and this accumulation is higher when cover crops are used (Franzluebbers, 2002). According to Giller *et al.* (2009), there is little evidence that reduced tillage *per se* leads to increased SOM contents and the benefits of enhanced SOM and soil fertility with CA are more a function of increased inputs of organic matter as mulch.

2.7.2 Improved N supply

Maize production in general is limited more by N deficiency than by any other nutrient (Arnon, 1975; Massignama *et al.,* 2009). The demand for N in maize gradually increases during growth and maximum rate of N absorption of up to 4.5 kg ha^{-1} per day occurs during the tasselling and silking stages (Ritchie, 1997). At grain formation, much of the maize N is translocated from the vegetative parts of the plant to the grain. Reid *et al.* (2001) reported that a typical maize crop requires absorption of about 450 kg N ha^{-1} with approximately 275 kg N ha^{-1} removed in the grain for a 15 Mg ha^{-1} grain yield.

Both grazing vetch and oat winter cover crops can affect N fertilizer management. Vetch cover crops fix atmospheric N and can reduce inorganic N fertilizer needs for succeeding cash crops (Clark, 2007). Woolly pod vetch, (*Vicia sativa*) can reduce optimum N rates for maize production by up to 200 kg ha^{-1} (Clark, 2007). Table 2.2 shows N fertilizer replacement values of different species of vetch cover crops. As the table shows, this N contribution is variable and dependent on environmental and management factors that affect the amount of dry matter (residue N) produced by the cover crop as well as the environmental and management factors that influence the yield potential of the maize.

Oat, with a high rooting density can be a catch crop during winter, trapping mineral N that would otherwise be lost to leaching (Clark, 2007).. Oat however, has a wide C:N ratio, especially when terminated late. A C:N ratio greater than 30 carries the potential for net immobilization of N and hence slow N release rate during mineralization (Pink *et al.,* 1948). Although climate, lignin, and cellulose content can affect crop residue N release rate, the C:N ratio is probably the most useful measure for determining the potential for N release during decomposition of winter cover crops (Bowen *et al.,* 1993). A C: N ratio of approximately 25 is used as a threshold delineating between mineralization and immobilization (Clark, 2007). The potential for immobilization of N from high C residues is greater with no-tillage than for conventional-tillage (Reeves *et al.,* 1986). Supplying an extra 25 to 30 kg N ha^{-1} to crops planted on residues of small grain cover crops is a good management practice for counteracting possible N immobilization (Reeves *et al.,* 1986; Touchton *et al.,* 1986; Verhulst *et al*., 2009). There is therefore a need to revisit the N management strategies when winter cover crops are included in rotations.

Table 2.2 Nitrogen content and fertilizer replacement (NFR) value of vetch winter cover crops in maize-based systems

Citation	**Cover crop**	**N uptake** (kg ha^{-1})	**NFR value** (kg ha^{-1})	**Dry matter** (Mg ha^{-1})
Hargrove (1986)	Hairy vetch	153	97	5.9
	Common vetch	134	61	5
Blevins *et al.* (1990)	Hairy vetch	103	75	4.6
Ebelhar *et al.* (1984)	Hairy vetch	209	100	5.8
Frye *et al.* (1988)	Hairy vetch	209	-	5.1
	Common vetch	134	-	4.3

Grazing vetch is a winter (cool season) cover crop and the most winter-hardy of the commercial vetches, though it may not survive a winter without a snow cover. The best time to plant woollypod vetch is during the winter months (Clark, 2007). However, higher biomass yields can be expected when grazing vetch is grown in winter under subtropical conditions, at higher elevations and frost free conditions. However, this may not necessarily translate into greater N contribution to the follow-up crops from the vetch cover crop. Warmer temperatures are associated with rapid decomposition and mineralization N during early stages of crop growth, including losses of N. In warm temperate regions of the EC, good growth and biomass yield (> 6 Mg h^{-1}) can be obtained from grazing vetch when compared with other winter cover crop species such as lupin (*Lupinus* sp.) (Murungu et al 2010a). As shown in the Table 2.2, N fertilizer replacement values for vetch cover crops can range between 130 and 210 kg ha^{-1} across different environments.

Release of N from oat residues can be much slower than grazing vetch (Fig 2.1). Nitrogen fertilization can be used to cause enhance decomposition rate for residues of wide C: N ratio such as oat (Touchton *et al.,* 1986). Under continuous practice of CA, the N immobilization may gradually diminish due to increased surface concentration of SOM, which acts as an N source and thereby effectively counteracting N limitations induced by high C residues. Nitrogen concentration in residue of small grains such as oat can be increased by fertilizing the cover crops with N (Clark, 2007). Early termination of oat also results in a narrower C:N ratio of the residue, but the total residue produced is reduced (Clark, 2007). If terminated too early, the narrower C:N ratio results in rapid decomposition of the residue, thus reducing duration of ground coverage. In practice, oat is terminated at the flowering stage to maximize biomass yield.

Incubation studies by Murungu *et al.*, 2010b, concluded that grazing vetch residues can potentially release adequate amounts of N to support early maize growth whilst oat may immobilize N, but for a short period(Fig 2.1).

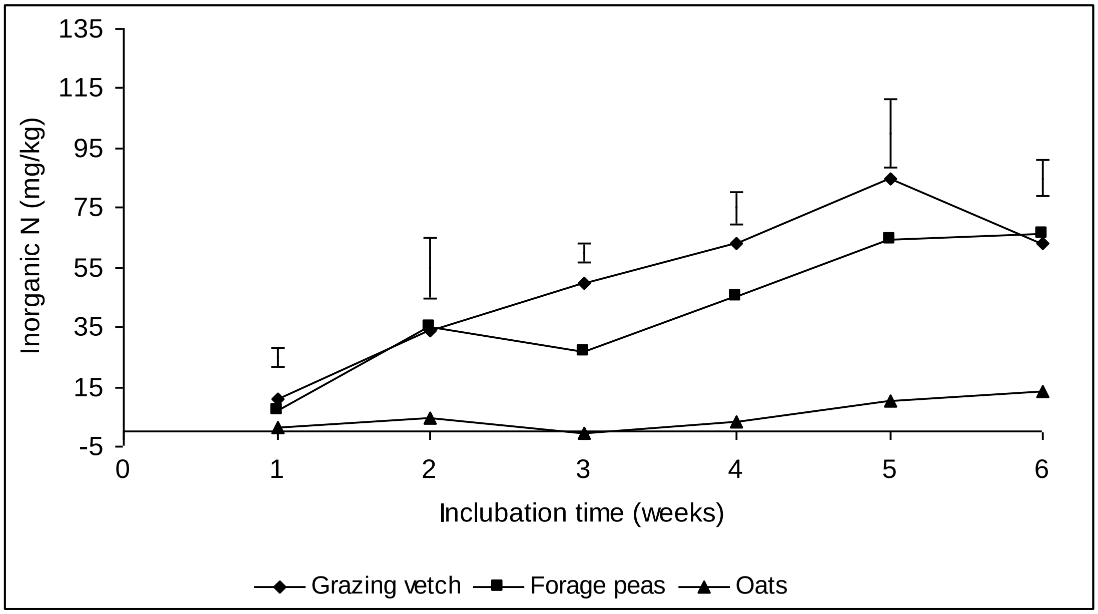


Figure 2.1 Net inorganic N mineralization from oat and grazing vetch residues incubated with soil under laboratory conditions. Source: Murungu *et al.* (2010b). Error bars represent the LSD at ($p<0.05$)

Meanwhile, no field studies have been carried out to substantiate this argument or determine how to manage N following both types of cover crops. The synchronization of residue N mineralization and crop uptake in the field is dependent on several factors, including soil, environmental and crop factors.

The N content of SOM can range from less than 0.5% to more than 6%, depending on biotic and abiotic ecosystem properties such as climate, soil depth, annual input of organic materials and soil mineralogy (Hassink, 1997). The C:N ratio of SOM in cultivated lands is frequently in the range of 10 to 12, implying that accumulation of

SOM must almost always be accompanied by increases in soil organic N (Hassink, 1997). The amount of increase in SOM therefore may correspond to the amount of N available either in the soil or in the material added (De Maria *et al.*, 1999). When soils receive crop residues of low N content, SOM will increase only as large as the N will permit (De Maria *et al.,* 1999). Restoration of SOM using winter cover crops could therefore be a problem of increasing both biomass input and the soil N level. Winter cover crops such as grazing vetch can fix N and tend to have a narrow C:N ratio (Table 2.3), and thus may be better able to support SOM increase on poor soils and under low N input as found in smallholder systems of the EC. Lignin and cellulose contents, through their effects on digestability, may also modify decomposability of residues and thus SOM accumulation. A positive N balance (fertilizer N - grain N export) is required to support SOM buildup in many systems (De Maria *et al.,* 1999). The lack of SOM accumulation under many no till systems of Brazil was attributed to the lack of sufficient external N input to the systems (Sisti *et al.,* 2004). Although insufficient N would hold back SOM accumulation, a similar effect may result if inorganic N is in excess. When large amounts of inorganic N are added to soil, the C:N ratio is reduced, thus favouring micro-organisms which eventually decompose the organic matter rapidly. There are increased losses of soil C as CO_2 to the atmosphere. This emphasizes the importance of good N management in order to effectively increase SOM content.

Table 2.3 Comparison of C:N ratio, cellulose and lignin contents between an oat and a grazing vetch cover crop

Cover Crop	C:N	C	N	Cellulose	Lignin	Citation
		g kg^{-1}				
Oat	33.6	412±3	12.3±0.4	349±2.2	43±0.8	Hu *et al.* (1997)
Woollypod vetch	13.3	427±3	32±0.9	288±3.7	84±1.1	
Oat	46.4	416±7	9±0.4	480±5.1	-	Murungu *et al.*
Grazing vetch	10.7	420±3	4±0.2	214±8.4	-	(2010b)

2.7.3 Phosphorus cycling

Phosphorus is the most important nutrient after N in optimizing maize growth, grain yield and quality (Bundy *et al.*, 2005). Total P removed by a maize crop of 12.4 Mg ha^{-1} grain yield is estimated at 52 kg ha^{-1} (Stevenson & Cole, 1999). Adequate P nutrition at the seedling stage in maize is probably the most critical, because deficiency at this stage cannot be remedied by side-dressing due to lack of P mobility in soils (Hedley *et al.*, 1995). Maize takes up P throughout the growing season, and the trend of P uptake during the grain formation is similar to that of N (Ritchie, 1997). If the concentration of P (on a dry weight basis) for maize exceeds 0.25%, it is considered sufficient (Hanway & Olsen 1980). However, if the P concentration is less than 0.20%, the plant is considered to be low in P and if less than 0.10%, the plant is considered to be very deficient. Very little or no yield increase from fertilizer application in maize can be expected when P content of the leaf exceeds 0.33% (Arnon, 1975). At maturity, about three quarters of the total P in the above ground parts of maize is in the grain. The response of maize grain to P is however not large compared to that of N fertilizer, because N deficiency places a larger constraint on grain yield than P deficiency (Steele, 1985).

Practically no P is added to soil by winter cover crops. Thus they only take up P from the soil solution and return it to the same soil. However, winter cover crops may enhance P availability, especially on the soil surface where large quantities of organic matter are returned. There are numerous reports suggesting that organic residues improve P availability and this is credited to more than one mechanism. According to Iyamurenye *et al.* (1996), application of organic material decreases P adsorption capacity of highly weathered soils through complexation of soluble aluminum (Al) and iron (Fe) by organic molecules. Organic carbon decreases P sorption (Ohno & Erich, 1997). Activity of soil microbes stimulated by decomposing cover crop residues produces carbon dioxide (CO_2) which reacts with soil water to produce carbonic acid, carbonates and the resultant changes in pH and increase in negative charges may increase orthophosphate desorption as well as dissolution of primary P-containing minerals (Brady & Weil, 2008). Crop residues generally favour buildup of labile inorganic and organic P at the expense of recalcitrant P when compared to inorganic P sources (Reddy *et al.,* 2001). According to Tiessen *et al.* (1984), P in many plant residues provides a relatively labile form of P to succeeding crops to supplement soluble inorganic P pools. Phosphorus has also been shown to accumulate in soil surface strata under zero-till regimes, not only due to the management effect of broadcasting or row applying P fertilizer rather than incorporating it, but also due to decomposition of P-containing residues on the soil surface and the slow movement of P through the soil profile (Franzluebbers & Hons, 1996).

Winter cover crops may also enhance P availability through their effects on reducing soil erosion. Sharpley & Smith (1985) summarized research on the effect of cover crops on total P losses and found that the reductions in total P losses ranged from 54 to 94%. They also pointed out, however, that the effects of cover crops on soluble P in runoff were more variable and did not always result in reductions.

Phosphorus in soils is in the form of organic (Po) and inorganic (Pi) (pools). These are either rapidly or slowly recycled in soils (Walker & Syers, 1976). Each pool can provide biologically available P to soil solution, but differ in the rate of P release. Bioavailable Pi released by P-containing primary minerals is transferred to the organic pool when it is incorporated into biomass, and eventually transferred to the SOM pool (Walker & Syers, 1976). Hedley *et al.* (1982) developed a P extraction method that uses a series of successively stronger reagents. This sequential extraction procedure generates Pi and Po pools with decreasing availability to plants. Resin-Pi, $NaHCO_3$-Pi and $NaHCO_3$-Po are the most labile pools. The NaOH extracted fractions are less labile, including inorganic P associated with Al and Fe oxides. The H_2SO_4-Pi fraction includes apatite and some other recalcitrant Ca phosphates. The labile organic P (Po) is a critical source of P in agroecosystems, representing an active reservoir of P (Tiessen *et al.,* 1994). The less available Po pools (other than residual P) can be also a better measure of potential plant available P, since these pools represent the soil P reservoir that can re-supply labile pools over time (Tiessen *et al.,* 1994). Sequential chemical fractionation can be used to obtain different biologically accessible pools of P.

There is an intimate link between SOM and Po and the proportion of Po of the total increases as the SOM content increases (Tate & Salcedo, 1988; Vitousek *et al.,* 2010).

Mineralisation of SOM provides plant-available Pi (Tate, 1985). The close relationship between C, N and Po contents in mature soils, and the special role that P has in controlling SOM through its effect on N fixation is a well established phenomenon (Walker & Syers, 1976). Organic matter accumulation and cycling may be controlled by P because appreciable increases in yields of dry matter usually result from a combination of N, P and K additions on many cropped lands.

2.7.4 Enriching the soil with essential mineral nutrients

In addition to N and P, winter cover crops can supply other essential nutrients to maize crops when their tissues decompose. Legumes such as vetch can explore subsoil nutrient pools and capture available nutrients through their extensive root systems (Gathumbi *et al.,* 2003). The enrichment of soil with essential nutrients varies with cover crop species, especially with quantity of dry matter produced and concentration of nutrients in the dry tissues. According to Franzluebbers & Hons, (1996), micronutrient cations (Zn, Fe, Cu and Mn) tend to be present in higher levels under zero tillage with residue retentions compared to conventional tillage due to surface placement of crop residues. With increased amounts of residues from high biomass yielding cover crops, it is expected that the micronutrients would be increased in even greater amounts. Deep rooted cover crops can mine nutrients from deeper profiles and increase their concentration in the surface soil.

When winter cover crops are actively growing, they remove water and soluble nutrients from the soil and this decreases the downward movement of water and nutrients in the soil. Because winter cover crops increase surface cover, they reduce nutrient losses and movement associated with soil erosion. Improved erosion control is one of the main benefits of winter cover crops (Kaspar *et al.,* 2001) because controlling erosion can prevent a significant loss of particulate nutrients with sediment. Therefore, for cropping systems with winter cover crops, it is assumed that annual fertilizer applications are lower or the same as what would be applied to the main crops without cover crops.

2.8 INTERACTIONS BETWEEN SOIL FERTILITY AND WEED MANAGEMENT

Apart from poor soil fertility, weeds are singled out by several researchers as another major cause of low maize yield in smallholder farmer systems of the EC (van Averbeke *et al.,* 1998; Jourbet, 2000; Fanadzo, 2009). Owing to poor weed management; soils in smallholder farming systems of the EC have built up large reservoirs of problematic weed seeds. *Digitaria sanguinalis, Cyperus esculentus* and *Cynodon dactylon* are problematic weeds causing abandonment of fields in the EC (Fanadzo, 2009).

Weed and soil fertility management complement each other. Thus the benefits of improved soil fertility may not be realized in the absence of good weed control and vice versa. Under poor weed management, it may be wasteful to fertilize. Using *Zanyokwe* irrigation scheme as a case study, Fanadzo (2009) reported that there were no responses to N fertilization owing to poor weed management in smallholder irrigation systems of the EC. In the absence of adequate weed control, N fertilizer promotes weed growth more than crop growth (DiTomaso, 1995). Kabambe & Kumwenda (1995) examined the interaction between weed growth and fertilizer use efficiency in some smallholder farmer systems of Malawi. They found that farmers who weeded twice at the critical periods for maize achieved a higher yield with half the amount of fertilizer, than farmers who weeded only once. It is obvious that the benefits of improved soil fertility may not be realized under poor weed management. This makes the development of soil fertility improvement strategies together with those for effective weed management critical in smallholder systems of the EC.

2.9 CONTRIBUTION OF WINTER COVER CROPS AND FERTILIZER TO NITROGEN AVAILABILITY AND PROFITABILITY OF MAIZE

Nitrogen fertilizer recommendations for maize in South Africa are based on yield potential data obtained from N fertilizer response experiments (FSSA, 2007). Based on the FSSA (2007) simplified model, soils with a yield potential of 10 Mg ha^{-1} in the EC require an N application rate of 220 kg ha^{-1}. As alluded to earlier, winter cover cropping brings N stored in winter cover crop residues, which can affect N fertilizer recommendations.

Nitrogen contribution from a winter cover crop to the main crop can be estimated as the N fertilizer needed to obtain a yield equivalent to that following the winter cover crop without N fertilizer. Within this context, nitrogen fertilizer use efficiency (NUE) can also be calculated as the difference between fertilized and unfertilized plots (‘difference method’) (Dorberman, 2007). This method is simple and cost effective, making it partially suitable for situations where resources are limited (Doberman, 2007). Although more practical than the use of N isotopes, this method of calculating N contribution from cover crops does not discriminate between the N contribution effect of the cover crop and other effects of the crop (Dorberman, 2007). Nitrogen use efficiency indices include partial factor productivity (P*f*P) defined as crop yield per unit of N applied and agronomic efficiency (AE) of applied N defined as unit yield increase per unit applied N (Mosier *et al.,* 2004; Doberman, 2007). The P*f*P is an aggregate efficiency index that includes contributions to crop yield derived from uptake of indigenous soil N and applied N resources, as well as the efficiency with which N acquired by the plant is converted to grain yield (Doberman, 2007).

Hargrove (1986) suggested that grain N content of the following crop is a more appropriate measure of the N contribution of the cover crop. Chlorophyll meters are also used to diagnose N deficiencies during the vegetative growth of maize, or compare treatment effects on maize N uptake (Bullock & Anderson, 1998). The Minolta SPAD-502 is a simple, hand held light meter used to estimate leaf N in a rapid and non-destructive manner (SPAD is an acronym for soil plant analysis development). It determines the relative amount of chlorophyll present by measuring the transmittance of the leaf in two wave bands, 600 – 700 nm and 400 – 500 nm. It gives a reading in arbitrary units that is proportional to the amount of chlorophyll present. Numerous researchers have correlated SPAD values with maize N status and grain yield (Bullock & Anderson, 1998).

The additional production costs from seed, fertilizers, labour and irrigation water invested on winter cover crops has implications on the profitability of maize production. Smallholder maize farmers are likely to invest in winter cover crops for soil fertility improvement, only if fertility benefits from winter cover crops can compensate for additional costs of winter cover cropping through increasing profitability. It is therefore ideal that the farmers should apply N fertilizer rates that return the most profitable economic yield, where the yield gain from fertilizer application will more than pay for the invested fertilizer. Nitrogen response trials could be used to calculate the economic optimum N rate.

Marginal analysis can be used for calculating the marginal rate of return (MRR) between technologies, proceeding in a stepwise manner from a lower-cost technology to the next higher-cost technology, and comparing MRR to acceptable minimum rates of return (Perrin *et al.*, 1988). The procedure may thus be useful for determining the economic benefits of fertilizer application after having invested in winter cover crops, as well as determining the amount of fertilizer that will give the highest returns for maize grown after oat and grazing vetch winter cover crops.

2.10 CONCLUDING REMARK

In summary, the large body of literature reviewed so far corroborates the fact that oat and grazing vetch winter cover crops can be employed to enhance SOM and plant available nutrients, especially N and P. Proper management of fertilizer is one of the keys to maximizing benefits, especially for oat. The magnitude of benefit is also dependent on several management and environmental factors. Thus appropriate studies are required in order to quantify the significance of these effects in maize-based CA systems of the EC. Through their different effects on soil N, grazing vetch and oat require different management options for N fertilizer in order to maximize maize yield.

3 EFFECTS OF FOUR YEARS OF MAIZE-OAT AND MAIZE-GRAZING VETCH ROTATIONS ON SOIL ORGANIC MATTER

Abstract

A study was conducted to determine the effects of oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) winter cover crops and fertilization regimes on soil organic matter (SOM) in an irrigated maize-based conservation agriculture (CA) system following four years of continuous practice. Separate plots of oat and grazing vetch cover crops were grown in winter and maize was planted in all plots in the following summer season. The four fertilization regimes used were: (i) fertilizer applied to the cover crops and the maize crop (F1), (ii) fertilizer applied to cover crops only (F2), (iii) fertilizer applied to the maize crop only (F3) and (iv) no fertilizer applied (F4). This gave a 2 × 4 factorial plus control plots (weedy fallows) laid out in a randomized complete block design with three replications. Soil samples from 0 – 5, 5 – 20 and 20 – 50 cm depths were analyzed for total SOM, particulate organic matter (POM) fractions, hot water soluble C (HWC) and C-associated with water stable macro and micro aggregates (WSAC). While total SOM was more concentrated in the 0 – 5 cm soil depth across treatments, a lack of maize fertilization (F2 and F4 regimes) significantly ($p<0.05$) reduced the stratification ratio. Oat and vetch rotations had significantly higher ($p<0.05$) fine POM, coarse POM and HWC than weedy fallow rotations at 0 – 5 and 5 – 20 cm. When fertilized, oat was better able to support SOM sequestration in water stable aggregates at 0 – 20 cm whilst grazing vetch was more effective at 20 – 50 cm. The F3 regime had similar SOM levels as the F2. When no fertilizer was applied (F4 regime), there were significant ($p<0.01$) reductions in biomass input and total SOM on the oat-maize and weedy fallow-maize rotations, whereas the vetch-maize rotation did not respond, both at 0 – 5 and 5 – 20 cm. The findings suggested that in the low fertilizer input CA system, targeting fertilizer to the winter cover crop as opposed to the maize crop could give similar SOM response, with less fertilizer invested and that grazing vetch cover crops may be better suited to low N input CA systems for SOM improvement.

Keywords: Fertilizer management; maize; soil organic matter; winter cover crops

3.1 INTRODUCTION

Poor soil fertility is a major problem causing low maize grain yields (< 3 Mg ha^{-1}) in many areas of South Africa where smallholder irrigation is practiced (Fraser, 2003; Fanadzo *et al.*, 2010). In the Eastern Cape (EC) province, poor soil fertility is attributed to low geological reserves of essential plant nutrients, low soil organic matter (SOM), continuous maize monoculture (without adequate nutrient replenishment) and tillage induced soil erosion (Mandiringana *et al.*, 2005). Medium textured, shallow and highly erodible young soils derived from mudstones and shales, with very low SOM (< 1%), are widespread in the EC (Laker, 2004; Mandiringana *et al.*, 2005). Improvements in SOM can result in several benefits in these soils, including improved soil nutrient storage capacity, nutrient availability, biological activity, soil structure and resistance to erosion (Brady &Weil, 2008). Meanwhile, conservation agriculture (CA) is being promoted to reduce crop production costs, conserve soil and improve its quality in low input smallholder farming systems of the EC.

Conservation agriculture involves minimal soil disturbance, a permanent soil cover, and ecologically viable crop rotations. A permanent soil cover, through the use of cover crops and crop residue mulch retention, combined with reduced tillage could be the best management practice for SOM restoration and control of erosion (Derpsch, 2005; Hobbs, 2007). In tropical savanna regions of Brazil where the soils are of low agricultural potential, maintaining permanent soil cover with a thick layer of biomass (> 6 Mg ha^{-1})

derived from cover crops and crop residues is one of the key factors for SOM restoration and soil fertility improvement in CA systems (Bollinger *et al.,* 2007). Findings of recent studies carried out in irrigated maize-based smallholder CA systems of the EC suggest that grazing vetch (*Vicia dasycarpa*) and oat (*Avena sativa*) winter cover crops can produce in excess of 6 Mg ha^{-1} dry matter annually and this provides good cover, weed control moisture conservation and maize yield benefits (Murungu *et al.,* 2010a; Musunda, 2010).

Nitrogen fertilizer inputs are required in order to maximize cover crop biomass yields on start-up of CA (Murungu *et al.,* 2010a). Application of N-based fertilizers is often recommended to increase SOM, particularly on lands that have already experienced a significant loss of SOM as a result of cultivation (De Maria *et al.,* 1999). Fertilizer application to optimize grain production generally results in increased crop residue production and the lack of SOM accumulation under some no till systems of Brazil was attributed. A lack of sufficient external N input to the systems (Sisti *et al.,* 2004). Grazing vetch appeared ideal as a winter cover crop in irrigated maize-based smallholder CA systems in the EC because of its ability to fix N in low N soils, fast decomposition rates and rapid release of nutrients for the benefit of subsequent crops (Murungu *et al.,* 2010b). Oat on the other hand tends to give higher biomass yields and residue persistence, and consequently better soil cover against weeds and soil erosion (Murungu *et al.,* 2010a). There are differences in tissue chemistry (C: N ratio, lignin and polyphenol content) of oat and grazing vetch, which leads to different decomposition characteristics (Murungu *et al.,* 2010b).

The combination of reduced tillage and increased residue return to the soil through appropriate cover crop species selection and astute fertilizer application present the opportunity for SOM buildup in maize-based smallholder systems of the EC. However, limited studies have been carried out to systematically examine the effects of winter cover crop species and fertilizer management on SOM pools. The accumulation rate of SOM as well as its fractions depends on soil texture, precipitation and temperature (Amelung *et al.,* 1998; Brady & Weil, 2008). On a local scale, micro-environmental conditions that depend on factors such as micro-topography, surface cover components and land management dictate spatial differences in SOM (Polyakov & Lal, 2004; Sisti *et al.,* 2004; Ding *et al.,* 2005)

Whereas SOM restoration can be a slow process, it is of interest to study the dynamics of SOM through its mineralizable pools which are sensitive to changes in management. Soil organic matter stabilization in soil aggregates is the principal mechanism for sequestration of C (Tisdall & Oades, 1982). Increases in SOM under continual C input are generally associated with increases in C-rich macro-aggregates (Six *et al.,* 2002) and water stable macro-aggregates are enriched in recently deposited SOM (Angers & Giroux, 1996). Soil organic matter can be divided into a relatively inert non-mineralizable fraction associated with clay particles in soils, potentially mineralizable 'active' fraction which can be expressed as hot water soluble carbon (HWC) (Körschens *et al.,* 1990) and particulate organic matter (POM) (Cambardella *et al.,* 2001). A decline in the size of these fractions relative to total SOM is indicative of loss in inherent soil fertility (Swift & Woomer, 1993).

Vertical stratification of SOM pools is common when degraded cropland is restored with conservation tillage (Dick, 1983) and it is important to measure the degree of stratification as an indicator of soil ecosystem functioning (Franzluebbers, 2002). Mills & Fey (2004) used the term 'pedoderm' to describe those first few centimeters of soil in which certain properties are often more strongly expressed than in the remainder of the soil surface horizon in undisturbed systems. The objective of this work was to evaluate the effects of oat and grazing vetch winter cover crops, including fertilizer management strategies on SOM and its pools (HWC, POM and C-associated with water stable macro- and micro-aggregates {WSAC}) in a maize-based CA system after four years of continuous practice. The hypothesis tested was that high biomass yielding winter cover crops and appropriate fertilizer management would improve SOM in maize-based CA systems.

3.2 MATERIALS AND METHOD

Field trials were conducted at the University of Fort Hare research farm in the EC. The farm is located at latitude 32° 46′ S and longitude 26° 50′ E at an altitude of 535 meters above sea level. It has a warm temperate climate with mean annual temperature of 18.1°C and an average annual rainfall of 575 mm received mainly during the summer months (November to March). The soils are deep and of alluvial origin, classified as Haplic Cambisol (IUSS Working Group WRB, 2006) with 64.2% sand, 16.0% silt and 19.8% clay and dominated by mica in the clay fraction (Mandiringana *et al.*, 2005). The study was carried out as part of a four year field trial, originally established to elucidate the effects of winter cover crops species and fertilizer on biomass yield and weed suppression in a maize-based CA system (Murungu *et al.,* 2010a). Some selected chemical characteristics of the soil are presented in Table 3.1. The soil type and climate at the research farm closely resemble those of smallholder irrigators in the EC.

Table 3.1 Pre-trial SOM, pH and total elemental content of the soil studied (0-20 cm layer)

SOM	pH	N	P	K	Ca	Mg	Na	S	Fe	Mn	Zn	Cu
		g kg^{-1}								mg kg^{-1}		
<10g kg^{-1}	6.1	0.8	0.35	4.04	4.25	1.53	0.84	14.1	17.70	451	34	40

Source: Mandiringana *et al.* (2005)

3.2.1 Treatments and experimental design

This study was established on the 1st of June 2007. Oat (*Avena sativa* cv. Sederbrg) and grazing vetch (*Vicia dasycarpa* cv. Max) winter cover crops were planted with and without fertilizer. The fertilizer was applied at 10 kg P ha^{-1}, as a compound (6.7% N; 10% P; 13.3% K) at planting. Grazing vetch was inoculated with *Rhizobium legunominosarium* biovar *viciae* at planting. Oats were top dressed using lime-ammonium nitrate (LAN – 28% N) 7 weeks after planting (WAP) at a rate of 138 kg ha^{-1} to make a total of 45 kg N ha^{-1}. Control plots were with no winter cover crops and no fertilizer was included. The cover crops were planted at recommended seed rates of 90 kg ha^{-1} for oats and 35 kg ha^{-1} for grazing vetch (Clark *et al.*, 1994) into small furrows opened using hoes. Supplementary irrigation was applied to fields when necessary (amounts supplied are summarized in Table 3.2).

After they reached the flowering stage, the cover crops, including the weedy controls were terminated by rolling them with a tractor mounted roller and applying glyphosate (N-[phosphono-methyl] glycine, 360 g L^{-1}) at a rate of 5 L ha^{-1}. After three weeks, all plots were split in half and maize (cv. PAN 6479) was planted using hand operated '*matraca'* planters. No tillage was done. The maize rows were spaced at a distance of 90 cm and the plants at 30 cm to give a planting density of 37 000 plants ha^{-1}. The planters were calibrated to place the required fertilizer at about 4 cm from the maize seeds in fertilized plots. Fertilizer was applied at two levels (0 N kg ha^{-1} and 60 N kg ha^{-1}), mimicking smallholder irrigation farmer practice in the EC (Fanadzo *et al.*, 2010). A third of the maize N was applied at planting as a compound (6.7% N; 10% P; 13.3% K + 0.5% Zn) and the rest as LAN at 6 WAP planting by banding.

Table 3.2 Rainfall and irrigation water (mm) received during periods of summer maize and cover crops growth (2007-2011)

Month	[1]2007/8		[1]2008/9		2009/10		2010/11	
	Rainfall	Irrigation	Rainfall	Irrigation	Rainfall	Irrigation	Rainfall	Irrigation
Jun	43.6	30	14.9	30	20.5	20	48.3	30
Jul	16	20	2.5	40	53	10	16.8	45
Aug	20.6	50	68.1	20	15	40	12	60
Sept	5.1	40	5	50	25.3	20	9.1	0
Oct	56.9	0	25.2	20	56.4	30	65.7	15
Nov	38	20	59.5	20	50.8	20	62.3	40
Dec	124.7	20	99.9	20	42.5	40	122.6	15
Jan	104.7	0	60.6	30	103.2	0	103.2	15
Feb	96.5	20	112	0	40.2	40	40.2	30

[1]Source: Murungu *et al.* (2010a)

The splitting of the winter plots and application of two fertilizer levels to maize in the first cycle gave rise to four fertilizer regimes namely F1, F2, F3 and F4. The F1 treatments were fertilized in both winter and summer seasons. Fertilizer was only applied in winter cover crops with no fertilization in the subsequent maize for the F2 treatments. For the F3 treatments, there was no fertilization of winter cover crops while the summer maize was fertilized. No fertilizer was ever applied in the F4 treatments both in winter and summer seasons. There were thus two factors in the study; type of cover crop mulch and fertilizer regimes giving a 2 × 4 factorial plus control plots laid out as a randomized complete block design (RCBD) with three replications. The treatment combinations are presented in Table 3.3.

Table 3.3 The treatments used in the study

	Cover crop type	Fertilizer regime	Description	Total yearly input of fertilizer N ($kg\ ha^{-1}$)	P ($kg\ ha^{-1}$)
1	Oat	F1	Fertilizer applied to both maize and oat	105.0	40.0
		F2	Fertilizer applied to oat only	45.0	10.0
		F3	Fertilizer applied to maize only	60.0	30.0
		F4	No fertilizer applied	0.0	0.0
	Vetch	F1	Fertilizer applied to both maize and vetch	66.7	40.0
		F2	Fertilizer applied to vetch only	6.7	10.0
		F3	Fertilizer applied to maize only	60.0	30.0
		F4	No fertilizer applied	0.0	0.0
2	Weedy fallow	F3	Fertilizer applied to maize only	60.0	30.0
		F4	No fertilizer applied	0.0	0.0

1 = cover cropping; 2 = no cover crop (control)

Early weed emergence during maize growth was controlled using basagran (a.i.: thiadiazine 480 g L^{-1}) on all plots at 5 L ha^{-1}. After maize harvesting, maize stalks were rolled and glyphosate applied at 5 L ha^{-1}. Oat and grazing vetch cover crops were planted and managed as in the previous seasons. The trial was continued into the second, third and fourth years under the same experimental design, trial management and rotations.

3.2.2 Determination of above ground cover crop and stover biomass yields

At cover crop termination in every season, plant tissue samples were obtained from two quadrats measuring 35 cm × 35 cm for estimation of above ground biomass yield. The cover crops were harvested by cutting at the soil surface with scissors. Weeds and cover crops were separated and oven-dried to a constant weight at 65^{o}C and dry weight determined. Maize stover yield estimates were taken from a net plot of 6 m × 2 m from the two central rows after maize harvest.

3.2.3 Soil sampling and determination of SOM

Soil sampling was done from the inner two-thirds of each plot between the maize rows. Six random soil samples were collected from three depths (0 – 5, 5 – 20 and 20 -50 cm). This was done in all the plots using a graduated auger 7 cm diameter at the end of the 4th year (April 2011) after maize harvest. All samples were collected after clearing the litter layer. The six subsamples of each soil depth were bulked to a composite sample and transferred to the laboratory, where they were air dried, (visible organic debris removed), and ground (< 2 mm). The soil samples were analyzed for total organic C using the Walkely-Black method (Nelson & Sommers, 1982). Soil organic matter (g kg^{-1}) was determined from organic C using a conversion factor of 1.724, on the assumption that organic matter contains approximately 58% organic C (Nelson & Sommers, 1982). The stratification ratio was calculated from the SOM content at the 0 – 5 cm depth divided by that at 5 - 20 cm soil depth (Franzluebbers *et al.*, 2002).

3.2.4 Determination of organic carbon pools

Particulate organic matter was determined using the physical fractionation method (Cambardella & Elliott, 1992). Fifty grams of air-dried soil was dispersed with 100 mL of 5 g L^{-1} of sodium hexametaphosphate. The soil suspension was shaken for 1 h on an end-to-end shaker (Digital electromagnetic wet sieve shaker, Filtra vibración S.L model FTLVH-0150) and poured over a set of sieves (250 and 50 µm) with several deionized water rinses. The mixture remaining on the sieves was back washed into a glass beaker, dried at 60°C for 24 h, weighed, ground and analyzed for C using the Walkley Black method. Soil organic matter (g kg^{-1}) in the fractions was determined from the organic C using a conversion factor of 1.724 (Nelson & Sommers, 1982). This gave fine (POM_{50-250}) and coarse ($POM_{250-2000}$) particulate soil organic matter fractions. The POM results are expressed as a fraction of the original soil. The addition of the two fractions (POM_{50-250} + $POM_{250-2000}$) gave the total particulate organic matter (POM_T). The relative proportion particulate of organic matter (POM_R) was calculated as POM_T/ SOM. Non particulate organic matter (< 50 µm) was calculated from the difference between total SOM and POM_T.

Water stable aggregate protected organic C was determined using a multiple wet-sieving technique according to the procedure of Mutuo *et al.* (2006). Air-dried soil samples (50 g) were shaken in 300 mL water for 1 h on an end-over-end tumbler shaker at 50 rpm. This was followed by wet sieving through sieves with openings of 250 and 50 µm to give aggregates of two size fractions namely; large micro-aggregates ($WSAC_{50-250}$) and macro-aggregates ($WSAC_{250-2000}$). Free organic matter for the aggregate fractions was separated by flotation after transferring the aggregates of the respective size classes into a 5 L bucket filled with water. The aggregate fractions were oven-dried to constant weight at 105°C and subsequently finely ground and analyzed for total organic C using the Walkely-Black method.

Hot water extracts were obtained by boiling 20 g air-dried soil sample in 100 ml distilled water for 60 min under a reflux system. After cooling, the suspensions were centrifuged for 10 min at 2 000 *g* to obtain clear extracts (Chodak *et al.*, 2003). The total organic carbon in the soil extract was analyzed using the Walkely-Black method.

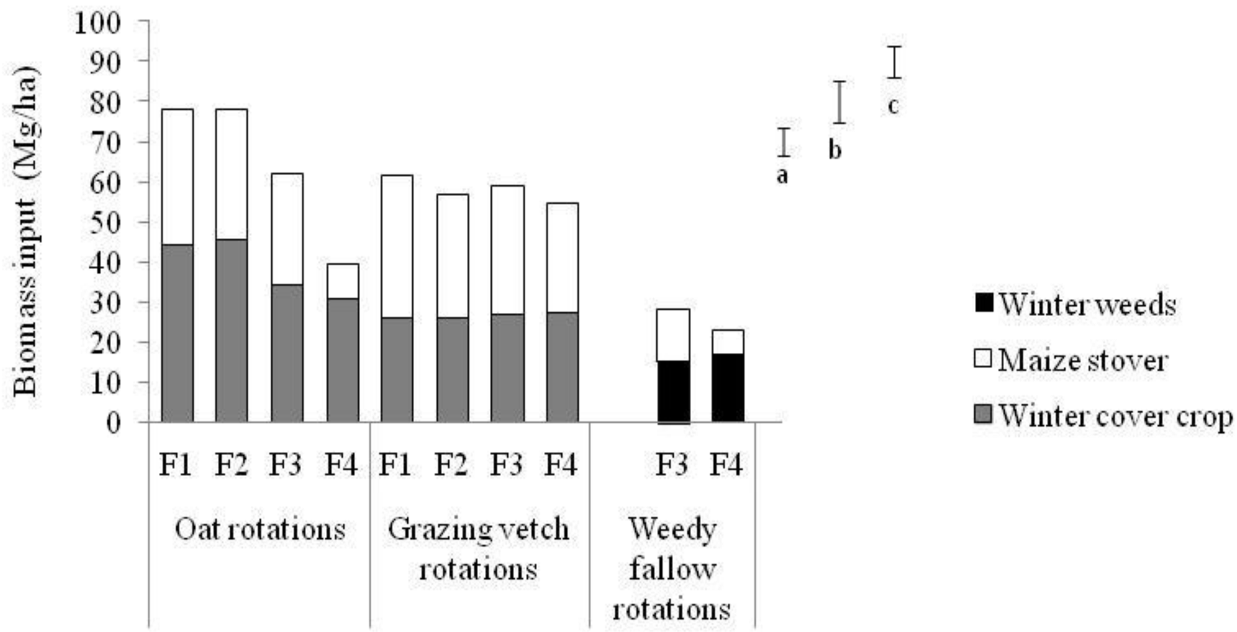
3.2.5 Data Analysis

Data, for all the parameters measured, were subjected to an analysis of variance (ANOVA) as an RCBD with 3 replications to test the effects of cover crop mulch and fertilization regime using GenStat Release 12.1 statistical software (Lawes Agricultural Trust, 2009). An extra factor (cover cropping) was included while cover crop type × fertilizer regime was nested within cover cropping to include analysis of controls in the ANOVA (Cochran & Cox, 1957). The ANOVA was separately performed for each soil depth. Where significant differences occurred, separation of means was done using the least significant difference (LSD) at the 0.05 level of significance.

3.3 RESULTS

3.3.1 Biomass production

There was a significant ($p<0.01$) interaction between cover cropping, cover crop type and fertilizer regime on pooled cover crop biomass and maize stover yields over the four-year period. While the fertilized oat-maize rotation gave higher biomass yield than the fertilized maize-vetch rotations, a lack of fertilization of the cover crops decreased biomass in oat-maize rotations while the vetch-maize rotations did not respond (Fig. 3.1). Fertilization of the cover crop as opposed to the maize (F2 versus F3 regime) gave higher biomass yield inputs on the oat rotations (Fig. 3.1). The lowest biomass yield was obtained from the weedy fallow rotations, in which the major weeds over the years were *Capsella bursa-pastoris, Malva parviflora, Sonchus oleracius* and *Stellaria media.*

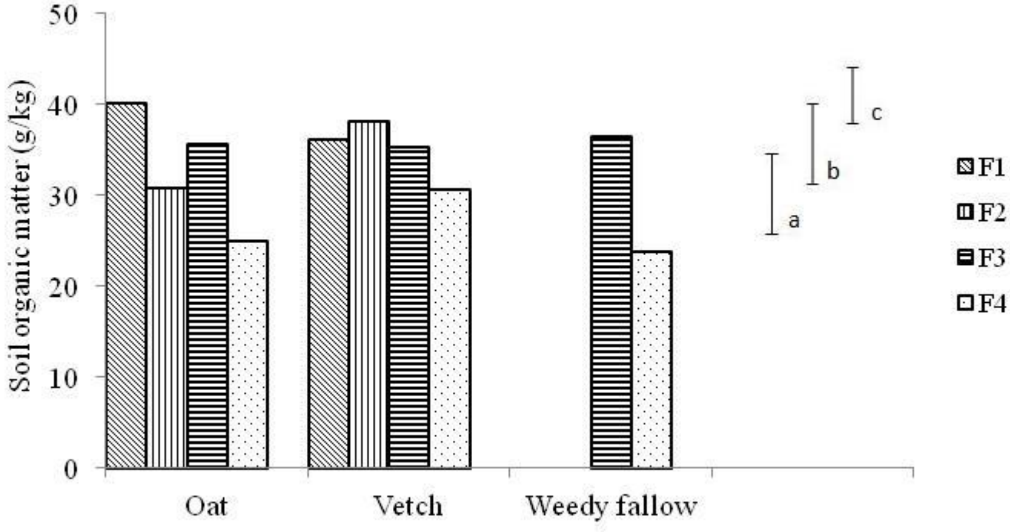


Error bar a = control to control (weedy fallow treatments) comparisons only, minimum replications; b = comparisons of controls with other treatments and c = treatment comparisons only, with controls excluded, maximum replications.

Figure 3.1 Cover cropping × cover crop type × fertilizer regime effects on total above ground biomass additions pooled for four years (excluding weed biomass in maize crop). Error bars represent the 5% LSD.

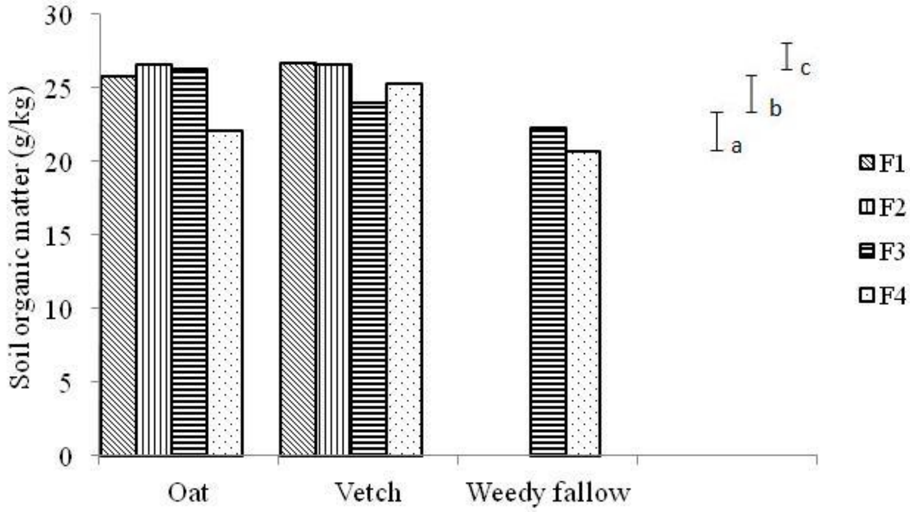
3.3.2 Soil organic matter content

The cover cropping × cover crop type × fertilizer regime interaction effect was significant ($p<0.05$) with respect to SOM at 0-5 and 5-20 cm soil depths, whereas all these factors had no effect at 20-50 cm. When no fertilizer was applied (F4-regime), there were reductions in SOM on the oat-maize and weedy fallow-maize rotations. However, fertilizer regimes had no significant effect on SOM for the vetch-maize rotation at 0-5 and 5-20 cm soil depths (Figures 3.2; 3.3). There were significant differences in SOM between the F1 and F2 regimes on the oat rotations but not on the vetch rotations. The F3 regime gave similar SOM levels as the F2 regime regardless of cover crop type. The F3 regime had similar SOM levels for oat, vetch and the fallow. The cover cropping × fertilizer regime interaction had a significant ($p<0.01$) effect on the stratification ratio of SOM. Fertilizer applied to maize only (F3 regime) resulted in higher stratification ratio on the weedy fallow (1.633) than on the winter cover crop (1.427) rotations. A lack of maize fertilization (F4 regime) reduced stratification ratio equally on both the weedy fallow (1.157) and winter cover crop (1.159) rotations. When SOM content at 0 – 5 cm was plotted against biomass input (Fig. 3.4), there was a positive linear relationship (r^2 = 0.434). The relationships at 5 – 20 cm and 20 – 50 cm were not significant.



Error bar a = control to control (weedy fallow treatments) comparisons only, minimum replications; b = comparisons of controls with other treatments and c = treatment comparisons only, with controls excluded, maximum replications.

Figure 3.2 Cover cropping × cover crop type × fertilizer regime effects on soil organic matter at 0 – 5 cm soil depth following four years of continuous practice



Error bar a = control to control (weedy fallow treatments) comparisons only, minimum replications; b = comparisons of controls with other treatments and c = treatment comparisons only, with controls excluded, maximum replications.

Figure 3.3 Cover cropping × cover crop type × fertilizer regime effects on soil organic matter at 5 – 20 cm soil depth following four years of continuous practice.

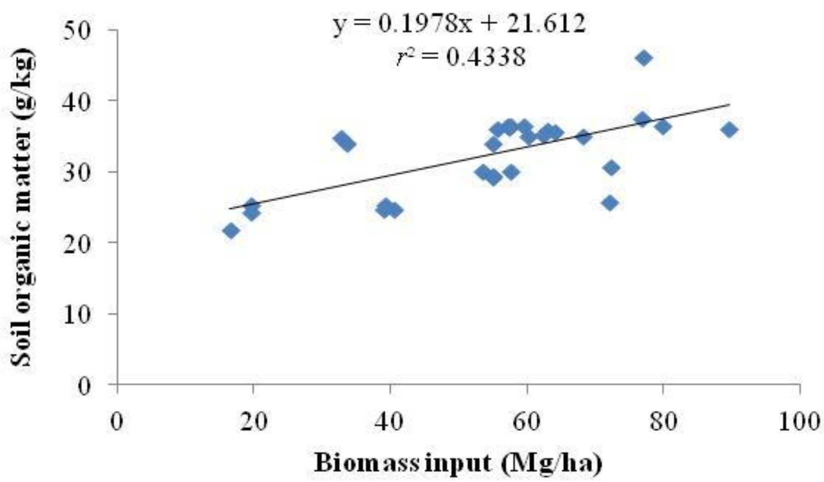


Figure 3.4 Relationship between total above ground biomass input and SOM at 0 – 5 cm soil depth following four years of continuous maize-cover crop rotation.

3.3.3 Particulate organic matter

Interaction effects of cover cropping, fertilization regime and cover crop type on POM fractions ($POM_{50\text{-}250}$, $POM_{250\text{-}2000}$ and POM_T) at all soil depths, were not significant ($p>0.05$), whereas the cover cropping effect was significant ($p<0.05$) (Figures 3.5; 3.6; 3.7). The oat and vetch rotations produced higher $POM_{50\text{-}250}$ levels than the weedy fallow treatments. At 20-50 cm, the cover cropping × cover crop type interaction was significant ($p<0.01$), with vetch giving higher $POM_{250\text{-}2000}$ (0.40 g kg^{-1}) than oat (0.12 g kg^{-1}) and weedy fallow (0.25 g kg^{-1}) rotations.

Cover cropping had a significant ($p<0.05$) effect on POM_T at 0-5 and 20-50 cm (Figure 3.5; 3.7) and cover cropping rotations had higher POM_T than weedy fallows. For non POM, the cover cropping × fertilizer regime interaction was significant only at 0-5 cm ($p<0.01$) (Table 3.4), which shows that F3 regimes gave higher non POM on the weedy fallow than the cover crops, while F4 regimes were similar.

Table 3.4 Cover cropping × fertilizer regime effects on non POM and $WSAC_{250-2000}$ ($g\ kg^{-1}$) in the 0-5 cm soil depth

	Winter cover crops				Weedy fallow		LSD_a	LSD_b	LSD_c
	F1	F2	F3	F4	F3	F4			
Non POM	20.34	15.95	19.05	12.8	25.31	14.51	6.57	5.69	4.65
$WSAC_{250-2000}$	0.795	0.803	0.770	0.456	0.335	0.244	0.202	0.205	0.167

LSD_a = for control to control comparisons only, minimum replications; LSD_b = for comparisons of controls with other treatments and, LSD_c = for treatment comparisons only, with controls excluded, maximum replications

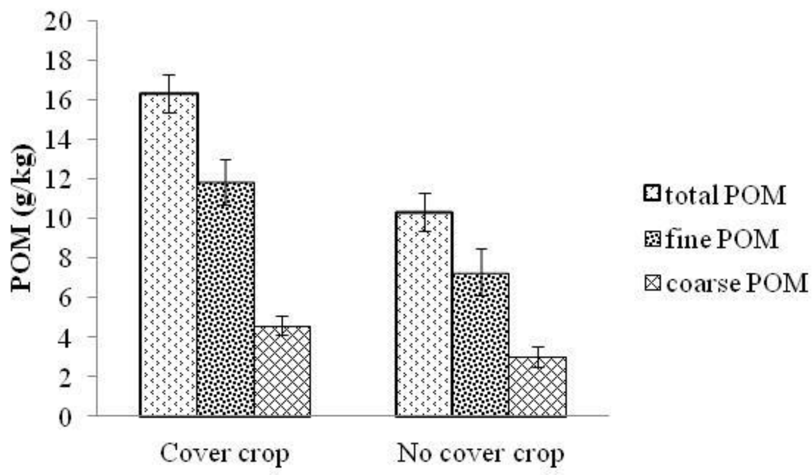


Figure 3.5 Effect of winter cover cropping on particulate organic matter (POM) fractions at 0 – 5 cm soil depth. Fine POM = 50 – 250 µm, coarse POM = 250 – 2000 µm and total POM = fine POM + coarse POM.

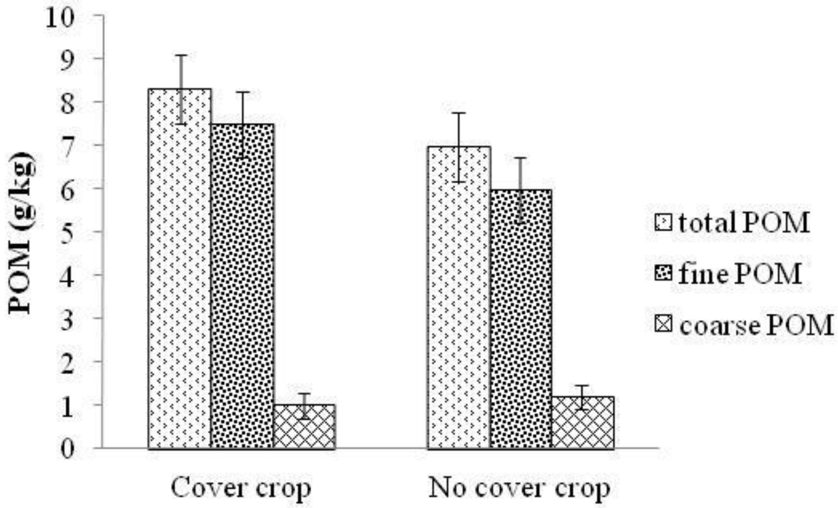


Figure 3.6 Effect of winter cover cropping on particulate organic matter (POM) fractions at 5 – 20 cm soil depth. Fine POM = 50 – 250 µm, coarse POM = 250 – 2000 µm and total POM = fine POM + coarse POM.

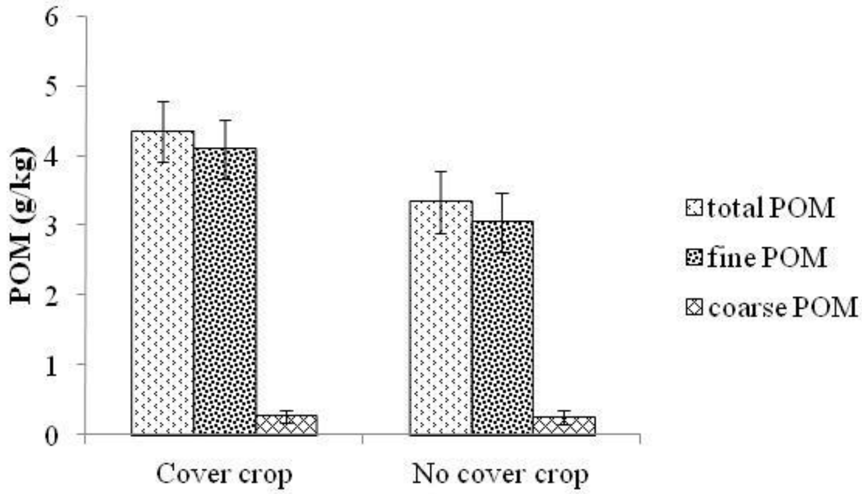


Figure 3.7 Effect of winter cover cropping on particulate organic matter (POM) fractions at 20 – 50 cm soil depth. Error bar represents LSD at 0.05 level of significance. Fine POM = 50 – 250 µm, coarse POM = 250 – 2000 µm and total POM = fine POM + coarse POM.

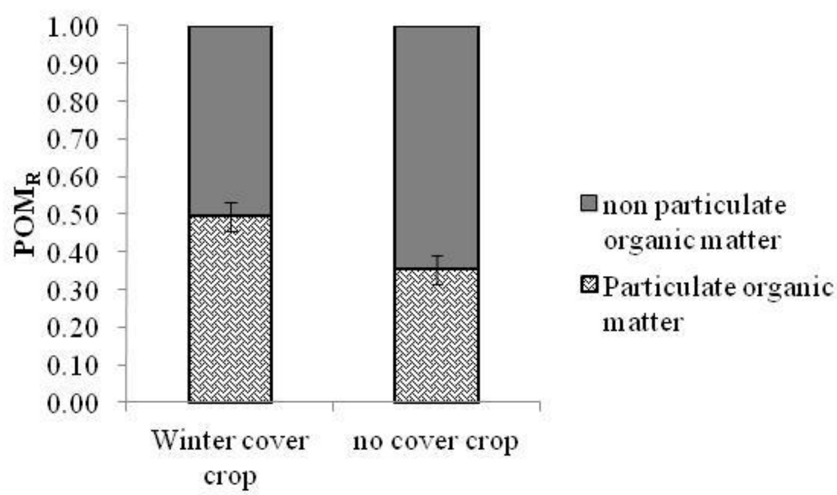


Figure 3.8 Effect of winter cover cropping on relative proportion of particulate organic matter (POM$_R$) at 0 – 5 cm soil depth.

3.3.4 Hot water soluble carbon

No significant ($p>0.05$) interactions were observed on HWC at 0-5 and 5-20 cm. However, cover cropping significantly ($p<0.01$) affected HWC. The weedy fallow rotations (no cover crop) gave lower HWC than the winter cover cropping rotations (Fig. 3.9). No treatment effects were observed on HWC at 20-50 cm.

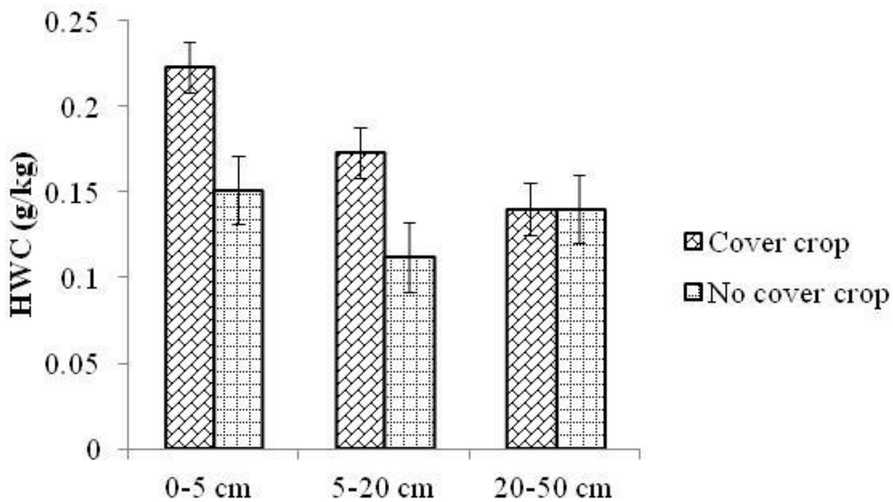


Figure 3.9 Effect of winter cover cropping on hot water soluble carbon (HWC) at 0 – 5, 5 – 20 and 20 – 50 cm soil depths. The no cover crop treatments are the weedy fallows.

3.3.5 Water stable aggregate protected carbon

Carbon protected in water stable micro-aggregates ($WSAC_{50\text{ -}250}$) at 0-5 and 5-20 cm was significantly ($p<0.05$) affected by the cover cropping × cover crop type interaction (Table 3.5). Oat rotations had higher $WSAC_{50\text{ -}250}$ than vetch and weedy fallow rotations. At 20-50 cm, all factors had no significant effect on $WSAC_{50\text{-}250}$.

The cover cropping × fertilizer regime interaction was significant at 0-5 cm. Winter cover cropping gave higher $WSAC_{250-2000}$ than weedy fallows. A lack of fertilization reduced the response in cover cropping rotations and the weedy fallow rotations did not respond (Table 3.4). The effect of cover cropping × cover crop type interaction on WSAC was significant at 20-50 cm. Grazing vetch rotations gave better response than either oat or weedy fallow rotations (Table 3.5).

Table 3.5 Cover cropping and cover crop type effects on water stable aggregate protected C (WSAC) pools

	Soil depth	**Cover cropping**		**Weedy Fallow**	**LSD_b**	**LSD_c**
		Oat	Vetch			
$WSAC_{50-250}$ (g kg^{-1})	0-5 cm	0.837	0.662	0.675	0.111	0.091
	5-20 cm	0.869	0.714	0.847	0.126	0.104
$WSAC_{250-2000}$ (g kg^{-1})	20-50 cm	0.128	0.176	0.115	0.055	0.045

LSD_b = for comparisons of controls with other treatments, minimum replication and maximum replications and, LSD_c = for treatment comparisons only, with controls excluded, maximum replications.

3.4 DISCUSSION

It has been demonstrated in this study that, in irrigated low-input systems as found in the EC, the levels of total SOM in the 0-20 cm soil depth can be increased from as low as 10 g kg^{-1} (Table 3.1) to ranges above 20 g kg^{-1} (Figures 3.2; 3.3) after four years of CA and 43.4% of the variation in SOM at 0-5 cm can be explained by differences in the amount of biomass input (Fig. 3.4). The longer periods of low temperature experienced in the warm temperate zones of the EC lessen decay and increase the rate of SOM accrual by carry-over from season to season compared to tropical areas (Brady & Weil, 2008). Howard & Howard (1990) estimated that soils with less than 2% SOC are prone to structural destabilization, erosion and crop yield reduction. The higher amount of SOM obtained in the top 0-5 cm compared to lower depths across all treatments (stratification ratios >1) was obviously due to the lack of incorporation of plant residue into the soil. However, a lack of maize fertilization reduced SOM stratification within the 0-20 cm layer or, in other words, increased the proportion of SOM in the lower profile. This is probably attributable to deeper penetration of roots as they seek nutrients.

The F3 rotations (fertilizer applied to maize only) received more N fertilizer than the F2 rotations (fertilizer applied to cover crop only). However, the results suggest that targeting fertilizer to the cover crop (F2) as opposed to the maize crop (F3) can give higher biomass yield input (for oat, Fig 3.1) and a similar SOM response, but with less fertilizer invested in this system. In terms of maize grain yield in the 1st and 2nd years of practice, responses were similar regardless of whether fertilizer was applied to winter cover crop only (F2) or maize crop (F3) (Murungu *et al.*, 2010). This suggests that for both benefits (maize and SOM), fertilizer is better invested on the winter cover crops. It is of note that resource-constrained farmers may not be willing to fertilize cover crops over maize crops for the sole purpose of SOM improvement. Some positive effects arising from investing small doses of N fertilizer on winter cover crops as opposed to maize crops can indeed improve cover crop biomass yields and quantities of residues. This could result in greater conversion of previously occluded nutrients into more mineralizable organic forms. Plate 3.1 illustrates biomass inputs from the fertilized oat and grazing vetch winter cover crops before (a and b) and after (c and d) termination.

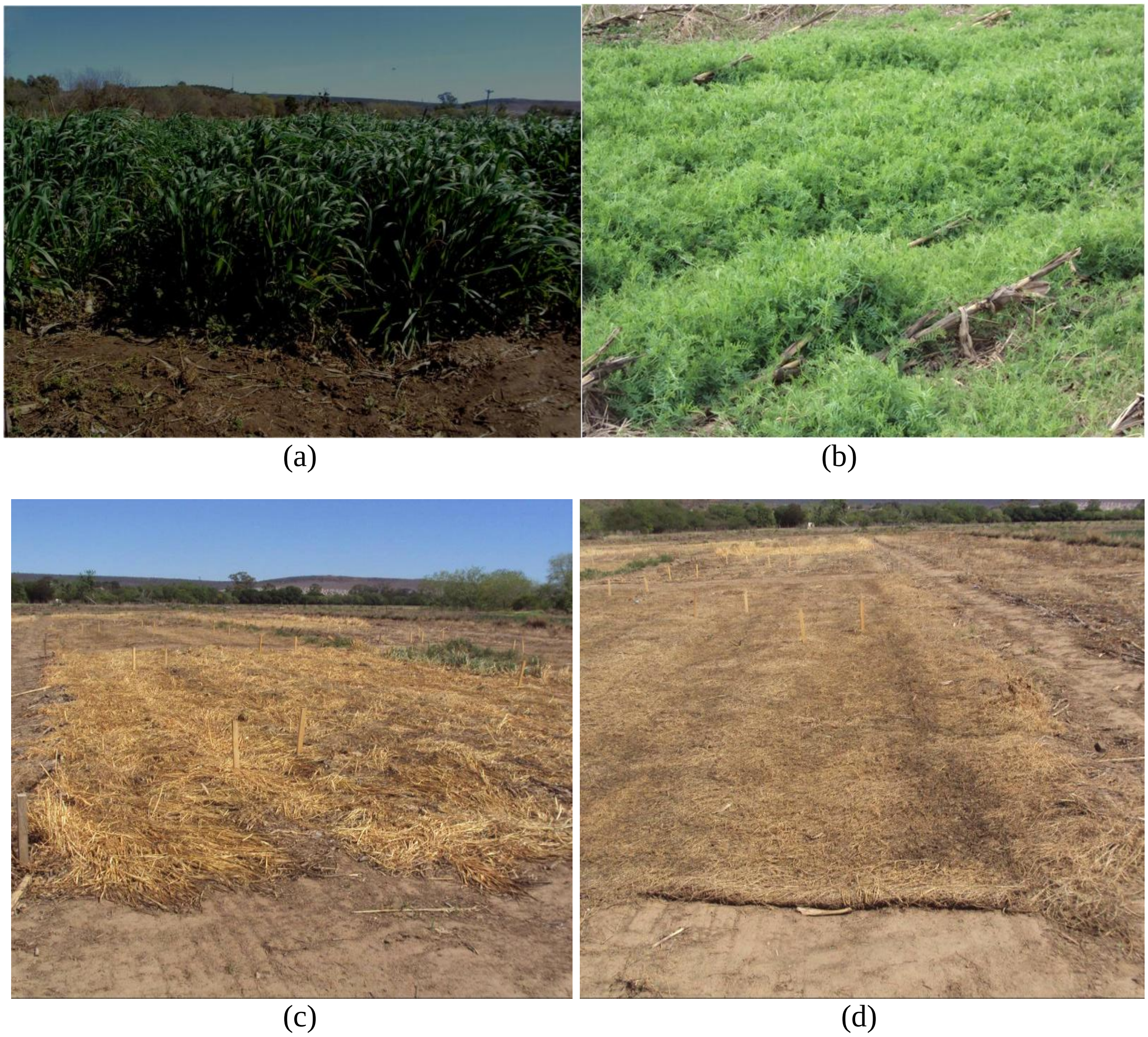


Plate 3.1 Biomass input from oat (a and c) and grazing vetch (b and d) before and after their termination respectively

Many researchers have concluded that the inclusion of cover crops in rotations improve the nutrient economy of cropping systems, with implications for fertilizer management and optimizing productivity (McVay *et al.,* 1989; Ibewiro *et al.,* 2000; Tian *et al.,* 2000). Lack of SOM response when 60 kg N ha^{-1} was applied to the maize crop following grazing vetch cover crops (F1 and F3 regimes) suggested that the N fixed by the cover crop could be enough and it may not be necessary to apply N following vetch cover crops for the purpose of SOM improvement. The results suggested that grazing vetch is an ideal cover crop for both SOM and maize yield improvement in low N fertilizer input smallholder CA systems of the EC.

On the other hand, a regression analysis of fertilizer N input and SOM at 0-5 cm for the oat cover crops shows a strong positive linear relationship (r^2 = 0.766, Fig. 3.10). This suggests that N fertilization is important for increasing SOM in oat rotations although less so for the N fixing vetch cover crops. This is in agreement with Fourie (2007) who reported that N fertilization increased biomass production for oat, with little increase observed for vetch owing to N fixation on a loamy sand soil in South Africa. Grazing vetch winter cover crops without additional fertilization in this study were estimated to fix approximately 346 kg N ha^{-1}, based on the N difference method (Murungu *et al.*, 2010b). A positive N balance (fertilizer N applied > grain N export) is required to support SOM buildup under CA (De Maria *et al.*, 1999).

Particulate organic matter is regarded as the fertilizer property of SOM (Swift & Woomer, 1993). A large proportion of the SOM at 0-5 cm across all treatments was in the particulate form as shown by POM_R results (Figure 3.8) which were consistent with findings by Motta *et al.* (2007) who investigated tillage and cover crop effects on soil quality and concluded that POM C accounted for 29 to 48 and 16 to 22% of soil organic C (SOC) for the 0 to 3 and 3 to 6 cm depths, respectively. The current study suggests that winter cover crops give higher amounts of POM than weedy fallows. Similarly, Ding *et al.* (2005) reported that both organic carbon and light fraction contents were higher in soils under cover crop treatments with and without fertilizer N than soils with weedy fallows. Grazing vetch and oat had consistently higher biomass yield than weedy fallows at cover crop termination, thus a greater source of POM. Winter cover crops would also have more extensive rooting systems for SOM contribution in deeper soil layers (Clark *et al.*, 1994). The reduced amount of maize stover yield and non-POM, where maize was not fertilized suggested that maize is the main contributor of non-POM, while winter cover crops are the main contributor of POM.

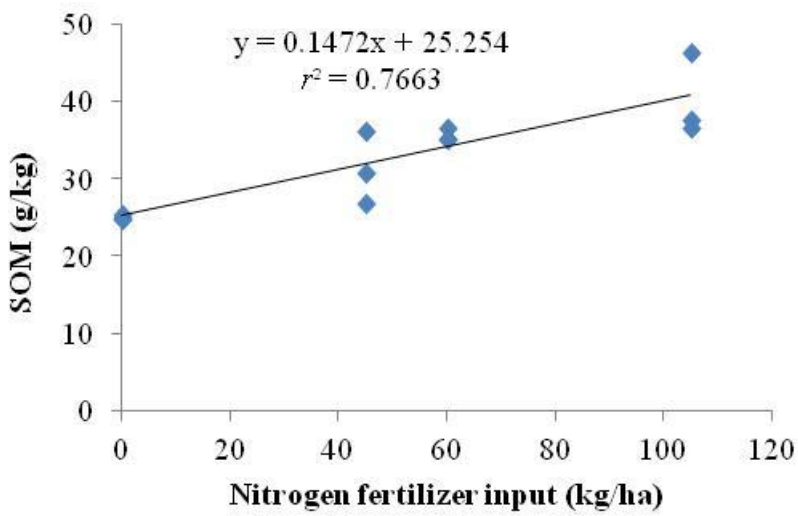


Figure 3.10 Relationship between nitrogen fertilizer input and SOM in the 0 – 5 cm soil depth for oat-maize rotations.

The higher amounts of HWC on the cover cropping treatments compared to weedy fallows in this study, suggested that the maize-cover crop rotations could be better able to supply N than the weedy fallow rotations. Körschens *et al.* (1998) recommended HWC as an integrated indicator of SOM quality due to its close relationship with microbial biomass, soil respiration and nitrate ion release in arable soils from a number of long-term plots where organic and mineral fertilizers were continuously applied.

Although the mechanisms affecting the sequestration of organic matter in soil aggregates are complex (Six *et al.*, 2002; Verchot *et al.*, 2010), results from this study suggest that oat cover crops are better able to support SOC sequestration in water stable aggregates than vetch cover crops or weedy fallows in the 0-5 and 5-20 cm soil depths. These results are consistent with findings by Basso & Reinert (1998) who concluded that black oat (*Avena strigosa*) cover crop induced higher water aggregate stability in the 0-5 cm depth than other cover crops, including common vetch (*Vicia sativa).* Carbon storage in soil aggregates is important in low clay content soils where SOM can be considered a major aggregate binding agent (Tisdall & Oades, 1982; Six *et al.*, 2002). The soil type on which the study was conducted has high sand and silt contents and mainly 2:1 clays.

Grazing vetch gave higher coarse POM and $WSAC_{250\text{-}2000}$ than oat at 20-50 cm and this is probably as a result of differences in rooting characteristics between the two winter cover crops. In the absence of soil mixing under reduced tillage, root biomass could be the important source of sub surface SOM. Below ground biomass generally contributes 9 to 13% of above ground biomass in cover crops and it constitutes an important source of C and N inputs for enriching organic matter (Shipley *et al.*, 1992; Sainju *et al.*, 2005). Below ground biomass yield, C and N contents tend to vary in similar patterns among cover crops as above ground biomass parameters (Sainju *et al.*, 2005). Although the rooting systems of both oat and vetch can extend up to 3 feet (90 cm) (Clark, 2007), oat tends to produce a more fibrous rooting system, with up to 90% of the roots localized in the top 0 – 30 cm whilst vetch has a tap root system.

3.5 CONCLUSIONS

The effects of winter cover crops on SOM are dependent on cover crops type and fertilizer management. When no fertilizer was applied, there were reductions in SOM and biomass input on the oat-maize rotation but not on grazing vetch-maize rotation. Targeting the fertilizer to the winter cover crops as opposed to the maize crop gave higher biomass yield input and similar SOM response but with less fertilizer investment. A lack of maize fertilization however reduced stratification of SOM in the 0 – 5 cm layer. Winter cover crops increase the easily mineralizable SOM fractions at 0 – 20 cm than weedy fallows. When fertilized, oat cover crops were better able to support SOM sequestration in water stable aggregates at 0 – 20 cm while vetch is more effective at 20 – 50 cm. Grazing vetch can support SOM increase better than oat in the absence of fertilizer, making it a better option for soil fertility improvement in low N input maize-based CA systems found in the EC province of South Africa. It would however, be necessary to establish how these cover crops and their effects on SOM could influence nutrient availability and maize yields.

4 WINTER COVER CROP AND FERTILIZER EFFECTS ON SOIL PHOSPHORUS POOLS IN A LOW INPUT MAIZE-BASED CONSERVATION AGRICULTURE SYSTEM

Abstract

The objectives of this study were to investigate; 1) the effects of winter cover crops (grazing vetch {*Vicia darsycapa*}, oat {*Avena sativa*}) and fertilizer application on surface soil Po and inorganic (Pi) pools following four years of continuous maize-cover crop rotations using sequential extraction and; 2) the relative importance of the P pools for maize P nutrition during early growth. Winter cover crop type had a significant ($p<0.01$) effect on microbial-P and HCl-Pi, but no significant effects on $NaHCO_3$-Po, $NaHCO_3$-Pi, HCl-Po, fulvic acid-P and H_2SO_4-P. Oat gave the highest microbial-P and weedy fallow gave the lowest HCl-Pi. Fertilized plots had significantly ($p<0.05$) higher $NaHCO_3$-Po (6.78 mg kg^{-1}) than non-fertilized (4.33 mg kg^{-1}). Weedy fallow gave the lowest total P, as well as labile and moderately labile P (45%) expressed as a percentage of total P, while oat and grazing vetch had similar percentages (55%). Lack of fertilizer increased humic acid P on oat and weedy fallow but had no effect on grazing vetch. Maize P concentration at 6 weeks after planting (WAP) was significantly reduced in the weedy fallow in comparison to the cover crops but was similar for oat and grazing vetch. There were strong positive relationships between HCl-Pi (r^2 = 0.89), $NaHCO_3$-Pi (r^2 = 0.81) and maize P concentration at 6 WAP, which means that these pools can be considered as parameters for predicting P supply to maize crops during early growth in the low P input CA systems. The results further showed that winter cover crop biomass input alone explained 73% of the variations in microbial P and 33% of total labile P, and thus microbial P should be considered as a management indicator of P availability on this soil. It was generally concluded that the inclusion of oat and grazing vetch winter cover crops in the low P fertilizer input CA systems increases P availability in the surface soil.

Keywords: Grazing vetch; maize; oat; phosphorus availability

4.1 INTRODUCTION

Phosphorus (P) deficiency is a widespread problem causing poor crop yields in smallholder farming areas of South Africa (SA) (Henry & Smith 2002; Mandiringana *et al.*, 2005). The global prices of P fertilizers continue to rise (Ward, 2008; Cordell *et al.*, 2009), resulting in further reduction in use of fertilizers by resource poor maize farmers. Therefore, it is becoming imperative to adopt strategies that conserve P and optimize its use. Conservation agriculture (CA) could conserve P resources through retention of crop residues and minimizing soil erosion.

In CA, no-till and permanent cover, through rotations and retention of crop residues, contribute immensely to soil quality and nutrient dynamics. A number of winter cover crops, which are legumes or small grains grown between regular grain crop production periods for the purpose of protecting and improving the soil, through their high biomass production, are known (Mannering *et al.*, 2007). Oat and grazing vetch are examples of such cover crops that have been proven to provide dependable amounts of biomass (> 6 Mg ha^{-1}), in maize based smallholder CA systems of SA, at least under irrigation (Murungu *et al.*, 2010a).

Through their extensive root systems, leguminous winter cover crops can explore subsoil nutrient pools (Gathumbi *et al.*, 2003), whereas grass species like oat can increase P uptake by both the cover crop and the succeeding maize (Karasawa *et al.*, 2002) through enhancement of viable mycelia of mycorrhizal fungi in soils. The high biomass yielding winter cover crops in CA systems have been found to increase surface soil organic matter (SOM) (Chapter 3) and there is a positive correlation between SOM and different P pools in soil (Harrison, 1979). Where organic matter is generated *in situ*, P may be immobilized in the SOM accumulated on the soil surface, especially if the C:P ratio is greater than 300:1 (Tate, 1985). In this case any mineral soil P becomes a component of microbial biomass. The soil microbial biomass may be considered as a reservoir of potentially plant-available nutrients, including P (Brookes *et al.*, 1984). Mineralization of organic P (Po) plays an essential role in P cycling and maintenance of plant-available P in low P fertilizer input cropping systems (Harrison, 1979; Tiessen *et al.*, 1994; Maroko *et al.*, 1999). The size of the Po pool that undergoes rapid mineralization contributing to plant available P over at least one growing season, known as labile P (Bowman & Cole, 1978; Ivanoff *et al.*, 1998), may be dependent on crop residue quality, soil and environmental characteristics, duration and type of cropping system (Lupwayi *et al.*, 2007).

A proportion of the organic matter returned to the soil annually becomes humified, with the P it contains, and decomposition of this fraction proceeds at a slow rate. A major challenge for low P fertilizer input in CA systems is, therefore, to increase surface SOM without substantial relocation of potentially available P resources to Po pools that are effectively unavailable for crop uptake. It is important to understand the effects of winter cover crops on P pools as a prognostic tool in the development of CA systems that allow resource poor maize farmers to apply less P fertilizer for maximizing maize yield.

A crop management field trial was established in 2007 at the University of Fort Hare in the Eastern Cape (EC) Province of South Africa, to evaluate winter cover crops species for biomass yield and maize yield response in irrigated and low fertilizer input CA systems (Murungu, 2010). This chapter reports on; 1) the effects of grazing vetch and oat winter cover crops and fertilizer application to the follow-on maize on surface soil P pools in the 4th year of continuous rotation with summer maize and; 2) the relative importance of the P pools for maize P nutrition during early growth.

4.2 MATERIALS AND METHOD

4.2.1 Experimental site, design and layout

The study was conducted at the University of Fort Hare Farm in an ongoing conservation agriculture field trial established in 2007 that is described in section 3.2. The climate and soil type of this site has also been described (Section 3.2). Pre-trial elemental content of the soil has also been presented in Table 3.1. The field trial management has been described in section 3.2.1. Two factors were studied, namely; winter cover crop type and fertilizer application to maize. The winter cover crops types were oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) plus a weedy winter fallow, all grown with no fertilizer. This gave a 3 × 2 factorial plus control plots laid out as a randomized complete block design with three replications.

4.2.2 Soil and plant sampling

Six random soil samples were collected from the organic matter rich 0 – 5 cm depth of each plot at the beginning of the 4th maize season (summer 2010) after cover crop termination using a small trowel. All samples were collected after clearing the litter layer. Soil sampling was done from the inner two-thirds of each plot. The six sub-samples were bulked to a composite sample and transferred to the laboratory, where they were air dried, visible organic debris removed, and ground (< 2 mm), before analysis of soil P pools. Two maize plants per plot from rows 2, 7 and 8 were sampled destructively at 6 weeks after planting (WAP), in the fourth year, by cutting near the soil surface. The plants were oven dried to a constant weight at 65°C and dry matter determined before being ground (< 2 mm).

4.2.3 Analysis of soil P pools

Soil P was separated into labile, moderately labile and non labile organic and inorganic pools following the modified sequential fractionation scheme (Kovar & Pierzynski, 2009) (Fig. 4.1) developed by Bowman & Cole (1978). Following fractionation, total P in all extracts was measured after persulfate digestion (Thien & Myers 1992). Organic P in the extracts was calculated as the difference between total P and inorganic P (Pi). Phosphorus concentrations in all extracts were analyzed by continuous flow-analysis (CFA) using the molybdenum blue colorimetric method (Murphy & Riley 1962) on a Skalar San Plus System (Breda, The Netherlands). Acid or alkaline extracts were neutralized prior to the P determinations.

4.2.4 Analysis of maize plant tissue P

Determination of tissue P concentration in maize plants was done using a wet digestion procedure with H_2SO_4 and H_2O_2 (Okalebo *et al.,* 2002). The concentration of P in the digests was also determined by continuous flow-analysis (CFA) using the molybdenum blue colorimetric method on a Skalar San Plus System.

4.2.5 Statistical analysis

All data for the different P pools and plant P concentration were subjected to an analysis of variance (ANOVA) as a factorial design to test the effects of cover crop type and fertilizer application on maize using GenStat Release 12.1 (Lawes Agricultural Trust, 2009). There were 3 cover crop treatments, namely; oat, grazing vetch and weedy fallow. Fertilizer was applied at two levels; (with and without fertilizer). Therefore, the general linear model for ANOVA was as follows:

$$Y_{ij} = \mu + \delta_i + \alpha_j + \beta_k + (\alpha\beta)_{ijk} + \varepsilon_{ijk}$$

Where: μ = grand mean

δ_i = effect of ith replication (i = 1, 2, 3)

α_j = cover crop type effect (j = 1, 2, 3)

β_k = fertilizer effect (k = 1, 2)

$(\alpha\beta)_{ijk}$ = interaction between cover crop type and fertilizer

ε_{ijk} = error component, independently and normally distributed with mean zero

Separation of means was done using the least significant difference (LSD) at the 0.05 level. Regression analysis was used to establish relationships between maize P concentration and P pools. Spearman correlation coefficients were determined with GenStat Release 12.1.

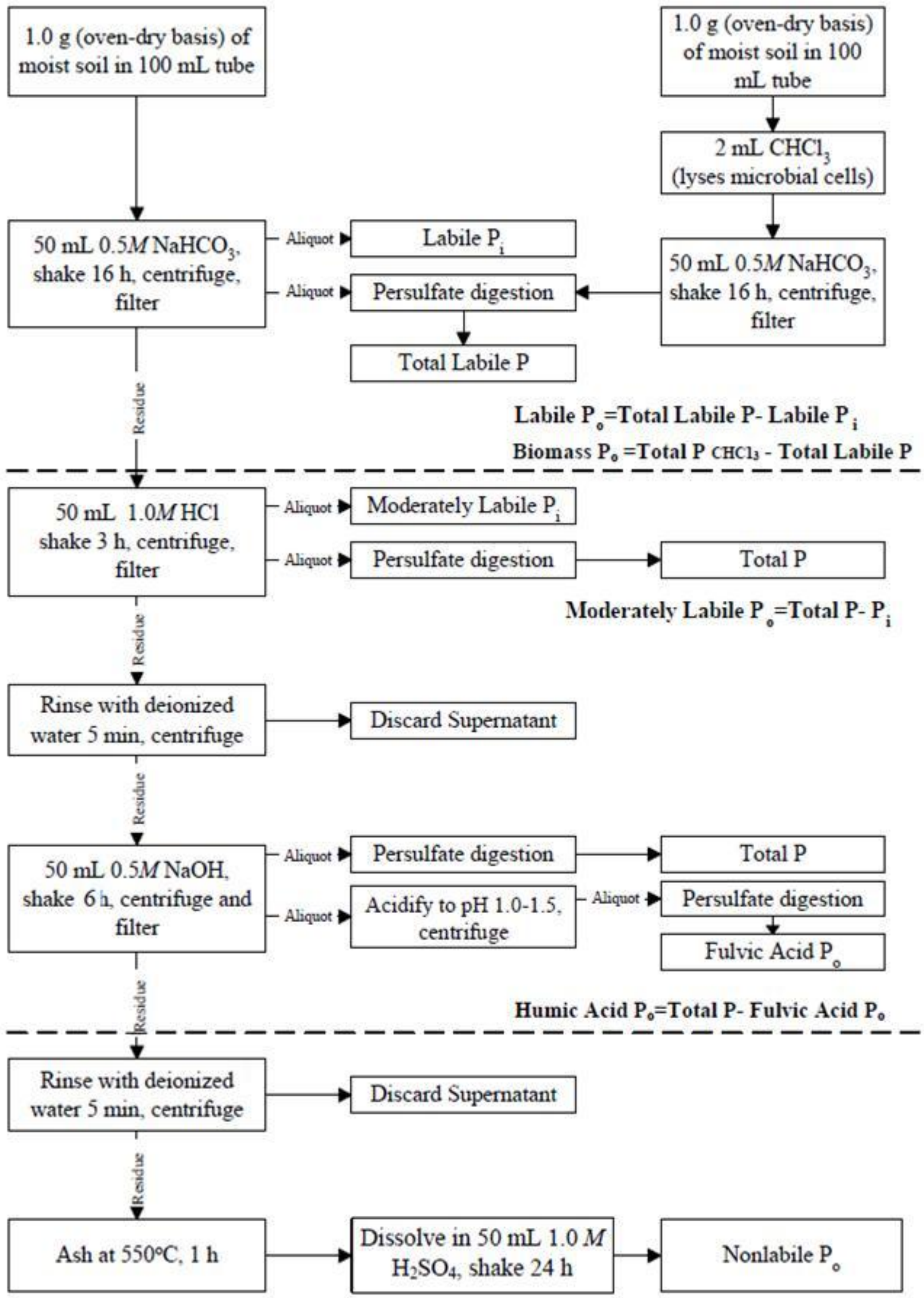


Figure 4.1 Sequential fractionation scheme for P (Kovar & Pierzynski, 2009)

4.3 RESULTS

4.3.1 Effects of winter cover crops and fertilizer on total soil P

Winter cover crop type × fertilizer interaction effect on total P was not significant ($p>0.05$) (Table 4.1). Cover crop type effects were however significant ($p<0.05$), with higher total P in soils from oat (619 mg kg^{-1}) and grazing vetch (634 mg kg^{-1}) treatments than the weedy fallow (524 mg kg^{-1}). Fertilizer effects were not significant ($p>0.05$) (Table 4.1).

Table 4.1 Analyis of variance for the effects of cover crop type and fertilizer on total soil P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block	2	236930.	118465.	27.50	
Cover crop type	2	42982.	21491.	4.99	0.031
Fertilizer	1	1326.	1326.	0.31	0.591
Cover crop type × fertilizer	2	6377.	3189.	0.74	0.501
Residual	10	43079.	4308.		
Total	17	330695.			

4.3.2 Effects of winter cover crops and fertilizer on soil P pools

Winter cover crop type × fertilizer interaction effects on all the labile and moderately labile P pools were not significant ($p>0.05$) (Table 4.2). However, winter cover crop type had a significant ($p<0.01$) effect on microbial-P and HCl-Pi, but not on $NaHCO_3$-Po, $NaHCO_3$-Pi, HCl-Po and fulvic acid-P (Table 4.2). Oat gave higher microbial-P than either grazing vetch or weedy fallow (Fig. 4.2). Oat and grazing vetch gave higher HCl-Pi than weedy fallow (Fig. 4.2). Winter cover crops also had a greater proportion of labile and moderately labile pools, expressed as a percentage of total P, than the weedy fallow treatment, which had a greater proportion of total non labile Po (Fig. 4.3). Fertilizer had no significant ($p>0.05$) effect on all the P pools except for $NaHCO_3$-Po (Table 4.2) for which the fertilized treatments had higher amounts (6.78 mg kg^{-1}) than the non-fertilized ones (4.33 mg kg^{-1}).

Table 4.2 Summary of analysis of variance (*F* values) of the effects of winter cover crop type (WCC) and fertilizer on phosphorus pools after four years of maize-winter cover crop rotation

		Labile to moderately labile organic (Po) and inorganic (Pi) pools						**Non labile Po pools**	
Factor	Df	$NaHCO_3$-Po	$NaHCO_3$-Pi	Microbial-P	HCl-Po	HCl-Pi	Fulvic acid-P	Humic acid-P	H_2SO_4-Po
Block	2	3.73 ns	23.02**	7.10 ns	0.17 ns	28.9**	1.06 ns	2.98 ns	3.22 ns
WCC	2	2.05 ns	1.67 ns	9.28**	0.12 ns	8.51**	0.48 ns	8.03**	0.97 ns
Fertilizer	1	6.56*	0.14 ns	0.27 ns	1.01 ns	0.01 ns	0.32 ns	0.00 ns	1.90 ns
WCC × fertilizer	2	0.34 ns	1.62 ns	0.10 ns	6.16 ns	0.23 ns	0.70 ns	10.17**	0.44 ns
Residual (MSE)	10	4.097	1165	29.26	9.342	713.8	233.6	67.42	210.8
Cv (%)		36.4	36.7	39.7	31.1	25.7	19.5	28.2	5.3

ns, not significant; *, **, significant at 0.05, and 0.01 probability levels, respectively

Winter cover crop × fertilizer interaction had a significant ($p<0.05$) effect on humic acid-P, but not on H_2SO_4-Po. Non fertilized oat treatment gave the highest amount of humic acid Po (50 mg kg^{-1}) while the fertilized weedy fallow gave the lowest amount (8 mg kg^{-1}) (Fig. 4.4). Whilst humic-P in the vetch treatment was not affected by fertilizer application as seen in Figure 4.4, those for the oat treatment and the weedy fallow were higher when unfertilized.

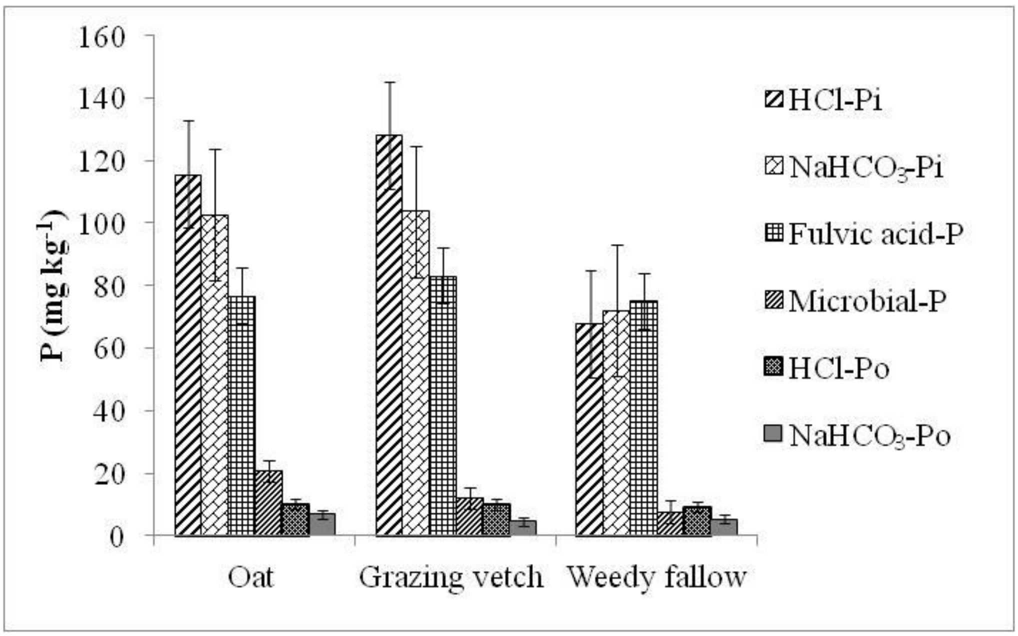


Figure 4.2 Effects of winter cover crop type on labile and moderately labile P pools. Error bars represent the 5% LSD.

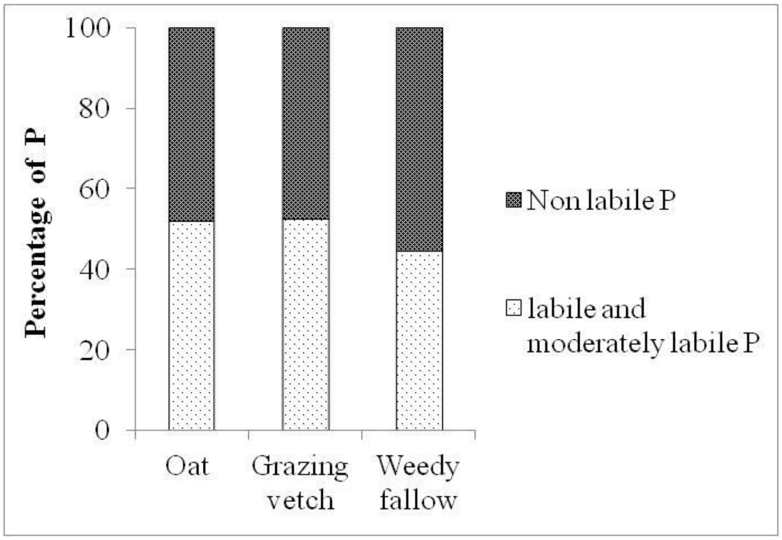


Figure 4.3 Effects of winter cover crops on the percentage of labile and non labile P fractions

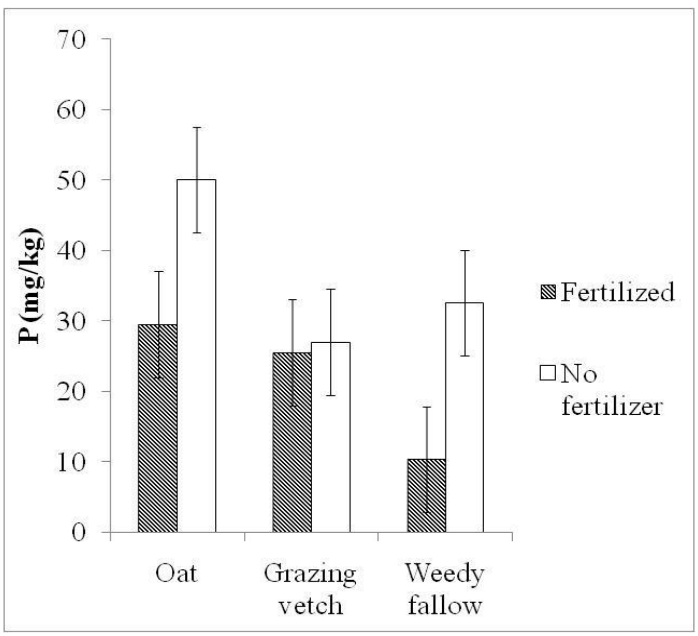


Figure 4.4 Interaction effects of winter cover crop type and fertilizer on humic acid-P. Error bars represent the 5% LSD.

4.3.3 Effects of winter cover crops and fertilizer on maize P concentration at 6 weeks after planting

Winter cover crop × fertilizer interaction effect, on maize P concentration (mg kg^{-1}), was not significant ($p>0.05$) at 6 WAP. However, winter cover crop type effects were significant with the weed fallow having a lower P concentration (Fig. 4.5) than oat and grazing vetch treatments, which were similar.

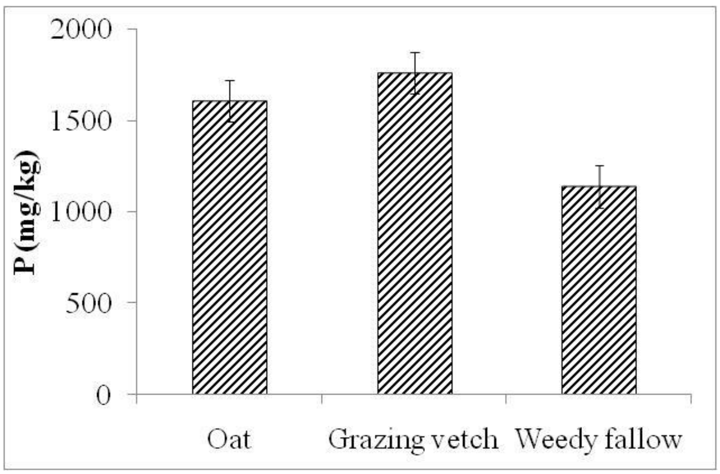


Figure 4.5 Effects of winter cover crop type on P concentration in maize at 6 weeks after planting

4.3.5 Relationships between labile to moderately labile phosphorus pools and maize P concentration

Regression analysis showed strong positive curvilinear relationships between HCl-Pi (r^2 = 0.90), $NaHCO_3$-Pi (r^2 = 0.81) and maize P concentration at 6 WAP (Fig. 4.6). Relationships of maize tissue P concentration with microbial-P, HCl-Po, $NaHCO_3$-Po and fulvic acid-P were generally weak or insignificant (Fig. 4.6). Spearman’s rank correlations coefficients between winter cover crop biomass input (summed over four years) and soil P pools, and maize P concentration, are reported in Table 4.3. Total biomass accumulation (that is maize stover and winter cover crop biomass) was significantly ($p>0.05$) correlated with HCl-Pi, microbial P, total labile P and plant tissue P. Winter cover crop biomass input was significantly ($p<0.05$) correlated with humic acid P, total labile P, plant tissue P and at $p<0.01$with microbial P (Table 4.3). Correlations with other P pools were not significant ($p>0.05$). Winter cover crop biomass alone explained 73% of the variations in microbial P and 33% of total labile P.

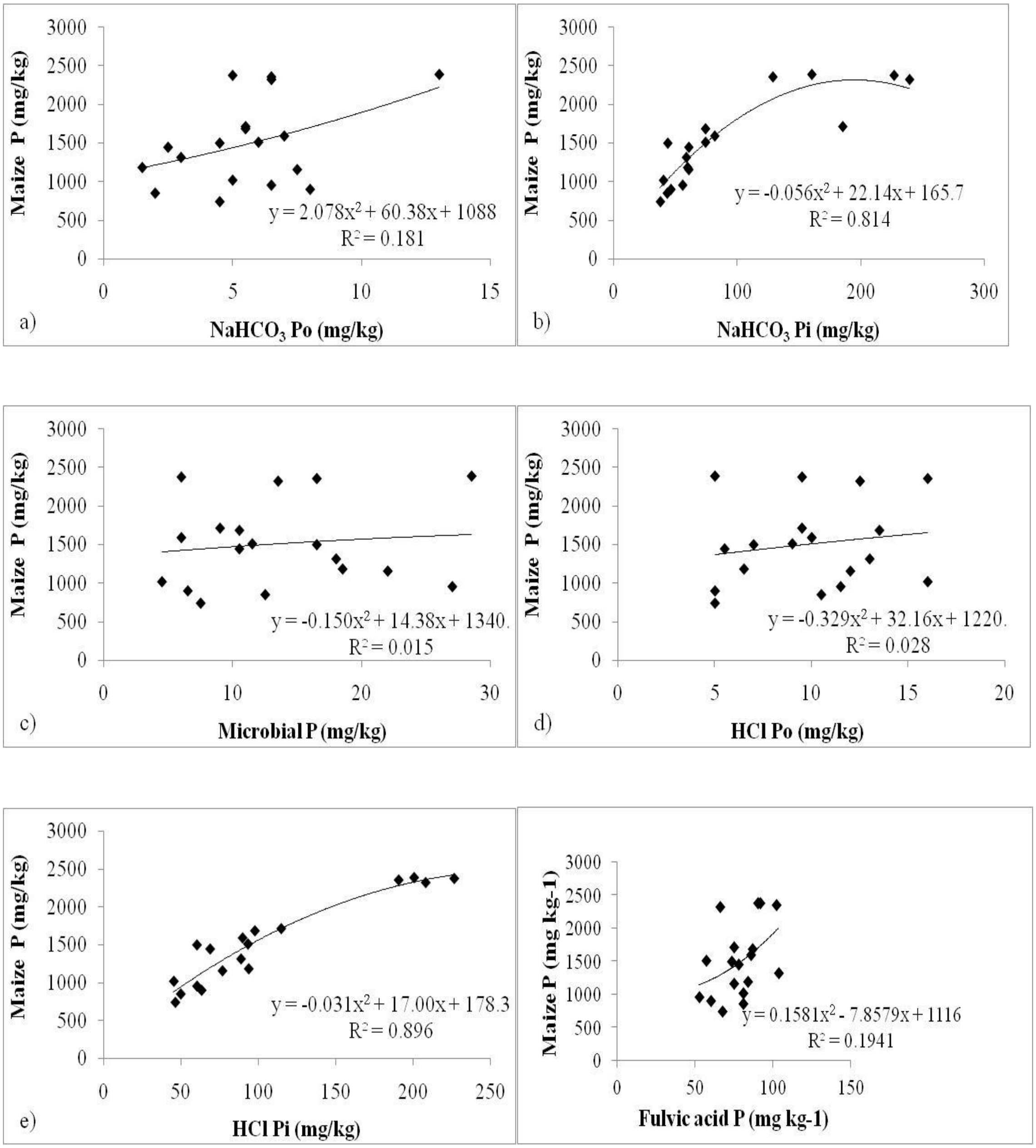


Figure 4.6 Relationships between $NaHCO_3$-Po (a), $NaHCO_3$-Pi (b), microbial-P (c), HCl-Po (d), HCl-Pi (e) and fulvic acid-P with maize P concentration at 6 WAP

Table 4.3 Spearmans rank correlation matrix for winter cover crop biomass and maize stover input (summed over four years) versus phosphorus pools and maize plant P concentration

	Winter cover crop biomass accumulation	Total biomass accumulation (maize stover + winter cover crop biomass
$NaHCO_3$-Pi	0.211 n.s	0.26 n.s
HCl-Pi	0.288 n.s	0.379*
$NaHCO_3$-Po	0.175 n.s	0.1 n.s
Microbial-P	0.73**	0.528*
HCl-Po	0.059 n.s	-0.027 n.s
Fulvic acid-P	0.042 n.s	0.213 n.s
Total labile P	0.33*	0.399*
Humic acid-P	0.353*	0.1 n.s
H_2SO_4-Po	-0.22 n.s	-0.154 n.s
Total P	0.228 n.s	0.251 n.s
Plant tissue P concentration	0.327*	0.47*

ns, not significant; *, **, significant at 0.05, and 0.01 probability levels, respectively

4.4 DISCUSSION

The higher total P in the cover crop treatments when compared with the control could be explained by the high biomass input in these treatments (Section 4.3.1). Coupled with fertilizer added to the maize, winter cover crop residues can be a source of P mined from larger soil volumes through their deeper root systems and association with mycorrhizal fungi (Gathumbi *et al.*, 2003; Karasawa *et al.*, 2002). When the cover crops and the follow on maize are terminated, the crop residue P contributes to the total P levels in the surface soils of no-till systems. The soil P occurs in different pools which vary in the level of availability to plants.

Bicarbonate extractable P ($NaHCO_3$-P) and microbial biomass-P fractions are considered to constitute labile P in the soil (Hedley *et al.,* 1982, Brookes *et al.,* 1984). Over half of plant litter P is considered water soluble and can be released to the soil as an initial flush of Pi with rainfall or irrigation (Schlather, 1998). If this comes before maize planting, the P is most likely to remain in the soil solution or be used for synthesis of microbial tissue. The higher microbial biomass P in the cover crop treatment could be the result of decomposition of the high biomass of oat and grazing vetch when compared to the weedy fallow. Microorganisms take up the mineralized P and release it when they die, making the P available to plants.

Bicarbonate is thought to solubilize P that is adsorbed on surfaces of crystalline P-compounds, carbonates and oxides of Fe and Al (Tiessen & Moir, 1993). The lack of significant differences in bicarbonate-extractable P fractions ($NaHCO_3$-Po, $NaHCO_3$-Pi) among the cover crop treatments could be a result of the low contents of crystalline minerals like carbonates and oxides of Fe and Al (Pavinato *et al.,* 2009) in the relatively young Haplic Cambisol used for the study. $NaHCO_3$-P also includes the soluble P, which is often detected using ion exchange resins (Tiessen & Moir, 1993). In weakly weathered soils that have moderate to low P fixation capacity, such as the Haplic Cambisol used in this study, repeated application of organic residues could saturate the P sorption sites, thus altering the chemical equilibrium established by adsorption/desorption processes, thereby resulting in increased amounts of P in the soil solution.

The high levels of the inorganic pool of HCl-P fraction in the cover crop treatments suggest that, when the large biomass decomposes, a greater proportion of the mineral P produced forms calcium phosphates (Pavinato *et al.,* 2009), and a portion is immobilized by soil microbial biomass. Dissolution of these phosphates makes moderately labile P (HCl-P) available to crops (Agbenin & Tiessen 1995). Decomposition processes which are stimulated when the cover crops are killed and left in the soil can further increase P availability by releasing CO_2, which forms H_2CO_3 in the soil solution, resulting in the dissolution of primary P-containing minerals (Tisdale *et al.,* 1985, Sharpley & Smith, 1989) and the secondary calcium phosphate formed from products of decomposition. Although the fulvic-P is also considered moderately labile, it did not respond to either cover crops or fertilizer in our study.

Fertilized treatments had higher amounts of $NaHCO_3$-Po (6.78 mg kg^{-1}) compared to the non-fertilized (4.33 mg kg^{-1}). Pavinato *et al.*, (2009) reported that $NaHCO_3$-Pi was increased by fertilization, as opposed to the organic pool observed in our study. However, when no fertilizer is applied, biomass production, a major source of P, tends to be lower, reducing the role of this pool in supplying P to crop plants. When the amount of P removed by crops exceeds P input from external sources, the deficit would have to be made up by the indigenous soil P pool if crop productivity is to be sustained. The major source of P in unfertilized low P soils is Po (Hedley *et al.,* 1982; Maroko *et al.,* 1999). Consequently, unfertilized soils may have lower amounts of Po than fertilized soils.

Although the humic-P and H_2SO_4-P are considered non-labile, their effects on the supply of plant available P in the future could be significant especially when the system attains equilibrium. This could be particularly important for cover crops used in this study (oat and grazing vetch). The high humic-P in the unfertilized oat treatment suggests an accumulation of humic acid fraction of organic matter which could have a significant contribution to soil aggregate stability in addition to being a reservoir of P. Winter cover crop biomass input was correlated with humic acid P (Table 4.3), suggesting that at least some component of the humic P was coming from the cover crops.

Non fertilized oat treatment gave the highest amount of humic acid Po while the fertilized weedy fallow gave the lowest amount and a possible reason for this is that fertilization increases decomposition of the humic acid fraction to form HCl-Pi and/or microbial biomass P and as such humic acid Po may not accumulate. The lowering of humic acid Po by unfertilized vetch when compared to oat (Fig 4.4) was possibly due to the ability of vetch to fix N. According to Arlauskiené *et al.* (2010), application of fertilizer generally increases the SOM mineralization rate and reduces humic acid content.

Results from this study suggest that available Pi was generally adequate across the treatments (i.e. $NaHCO_3$ Pi > 40 mg kg^{-1}) at the sampling depth of 0-5 cm when compared with critical Olsen 3 (0.5 M $NaHCO_3$) Pi values (5 – 15 mg kg^{-1}) as proposed by Olsen & Dean (1965). Under no till, P tends to be stratified and this may partly explain these high values of $NaHCO_3$Pi following four years of continuous no till and cropping. Increasing $NaHCO_3$Pi concentrations were associated with greater P concentrations in the young maize plants, but there was no response of maize P concentration to $NaHCO_3$Pi beyond 120 mg kg^{-1} (Fig. 6b).

P concentration in maize and biomass production of both cover crops and maize could be explained by the total labile and moderately labile P fractions (Table 4.3), which suggests that maize was depending on these pools for P. Correlation and regression analysis (Fig. 4.6) also showed that maize plant P concentration at 6 WAP was dependent to a large extent on labile and moderately labile Pi fractions i.e $NaHCO_3$Pi and HCl-Pi, and to a lesser extent on the labile Po fractions (microbial-P, fulvic acid-P, HCl-Po, and $NaHCO_3$-Pi). The results suggest that the labile Po fractions may be important to a lesser extent than the labile Pi fractions in terms of explaining maize P uptake during early growth. However, mineralized Po may play a more important role in the latter stages of crop growth when Pi sources are exhausted, or when decomposition of crop residues has proceeded to a greater extent. The contribution of the cover crops to the different soil P pools suggests that in the long term fertilizer P could be reduced in such systems.

4.5 CONCLUSIONS

In a maize-based CA system, on weakly weathered soil as found in the EC, oat and grazing vetch, as winter cover crops, and application of fertilizer to follow-on maize could increase the labile and moderately labile P pools in the surface soil when compared with the weedy fallow. These pools, particularly the HCl-Pi and $NaHCO_3$-Pi, were strongly correlated to maize P concentration and can be used for predicting P supply for early maize growth in low P input CA systems. Further work may be needed to evaluate the effects of winter cover crops on the different P pools in deeper soil layers and their seasonal dynamics. Increases in pools of plant available P in the surface soil with winter cover crops are just one important aspect of soil fertility improvement and it would be necessary to investigate the effects of the winter cover crops on the availability and uptake of other essential plant nutrients, including maize grain yield.

5 WINTER COVER CROPS AND FERTILIZER EFFECTS ON NUTRIENT AVAILABILITY AND UPTAKE, AND MAIZE YIELD IN A MAIZE-BASED CONSERVATION AGRICULTURE SYSTEM

Abstract

The objective of this study was to determine the effects of rotational oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) winter sown cover crops and small doses of fertilizer on nutrient availability, nutrient uptake and yield of a subsequent maize crop under a warm temperate climate in South Africa. After four years of continuous rotation, the winter cover crops had a significant ($p<0.05$) effect of increasing extractable soil Cu, Mn, P, and Zn but not on Ca and K. The NPK and Zn fertilizer applied to maize was also important for increasing extractable P and Zn, but had no significant effect on Ca, Cu, Mn and K. Grazing vetch increased soil mineral N, maize grain yield and grain N concentration more than either oat or weedy fallow but reduced extractable soil Mg. The fertilizer replacement value for grazing vetch was 73, 36, 49 and 1.8 (kg ha^{-1}) $year^{-1}$ for N, P, K and Zn respectively. Without fertilizer, there were sharp declines in maize yield on the oat and weedy fallow rotations over the four year period, but less so, on the grazing vetch. The findings suggested that grazing vetch had a high fertilizer replacement value, which resulted in maize yield improvement and maybe ideal for low fertilizer input maize based CA systems in the Eastern Cape Province of South Africa.

Keywords: Extractable nutrients; fertilizer replacement index; grazing vetch; maize yield; nitrogen; oat; phosphorus

5.1 INTRODUCTION

Soils in smallholder maize fields of the Eastern Cape (EC) are generally low or very low in available nutrients. This has been attributed to low soil organic matter (SOM) levels and low geological reserves of nutrients, notably P and Zn, coupled with continuous cultivation of lands without adequate nutrient replenishment (Mandiringana *et al.,* 2005). Conventional farming practices, based on extensive tillage, especially when combined with removal or *in situ* burning of crop residues, have magnified soil erosion mediated nutrient losses, land degradation and soil fertility challenges experienced by farmers. Despite the recommended mineral fertilizer rates of up to 220 kg N ha^{-1} for maize in the area (FSSA, 2007), use of inorganic fertilizers for improving maize yields by smallholder farmers is limited as the majority are resource poor (Fraser, 2003; Fanadzo, 2010).

Alternatives for improving soil fertility in the smallholder farming communities of the EC include application of cattle manure (Mkile, 2001), human urine (Mnkeni *et al.,* 2005), goat manure (Gichangi, 2008), cyanobacteria (Maqubela *et al.,* 2010) and composts (Mupondi *et al.*, 2010). More recently, the search for sustainable solutions to soil fertility challenges has focused on conservation agriculture (CA). The major principles of CA are reduced tillage, crop rotation and permanent soil cover through cover crops. Inclusion of cover crops in CA systems to replace bare fallow has implications on nutrient availability as they: (i) capture nutrients that would otherwise be lost to leaching (ii) extract nutrients from deeper layers and convert occluded mineral forms into organic forms and; (iii) fix and enhance N in soils deprived of N (only for legumes). Cover crops also add SOM (Chapter 3), which increases the cation exchange capacity and contributes to a greater ability to hold available plant nutrients (Brady & Weil 2008). The degree to which a particular cover crop meets these specifications may be dependent on soil, climate, succeeding cash crop as well as characteristics of the winter cover crop itself.

In warm temperate regions such as the EC, cropping a winter cover crop behind a summer maize crop is possible as an entry point into CA. The need to promote winter cover crops in irrigated low input maize-based smallholder systems of the EC for soil cover, as well as SOM build up, nutrient cycling and weed control has been well recognized (Murungu *et al.*, 2010a; Murungu *et al.,* 2010b; Musunda, 2010). Grazing vetch and oat are examples of fast growing, winter hardy cover crops, which have been tested to provide dependable biomass and SOM in these systems (Chapter 3). Grazing vetch appears ideal for low fertilizer input systems because of its ability to fix N, to decompose quickly and to rapidly release nutrients. On the other hand, oat produces less easily decomposable residues, thus offering better soil protection against weeds and erosion.

Long-term experiments are the primary source of information to determine the effects of cropping systems and soil management on soil productivity. An experiment was established in 2007 to determine the effects of oat and grazing vetch winter cover crops and fertilizer application to maize on biomass input and weed suppression in an irrigated maize-based smallholder CA system of the EC (Murungu *et al.,* 2010a). Information on the effects of the cover crops on nutrient availability, maize yield and their fertilizer value under continuous practice is lacking. Results from four years of continuous CA under this experiment (Chapter 3) suggested improvements of SOM and its different pools. Organic matter and some of its pools are closely associated with nutrient availability. This chapter reports results from the effects of rotational winter cover crops and fertilizer on nutrient availability, maize nutrient uptake and yield after four years of continuous practice from the same trial.

5.2 MATERIALS AND METHOD

Field trials were conducted at the University of Fort Hare research farm, in the EC province of South Africa. The location, climate and soil type of this site has been described previously (Section 3.2).

5.2.1 Experimental design and field trial management

The study was part of a four year field trial, originally established to determine the effects of winter cover crop species and fertilizer on biomass input and maize yield in a maize-based CA system as reported in Chapter 3. Two factors were studied, namely; winter cover crop type and fertilizer application to maize. The winter cover crops types were oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) plus a weedy winter fallow, all grown with no fertilizer. This gave a 3 × 2 factorial laid out as a randomized complete block design with three replications. Agronomic details of the trial have been described by previously in section 3.2.1. Birds, snails and slugs which appeared in outbreak proportions in the 3rd and 4th years were controlled by physical manning of the fields during early emergence (birds), and a combination of snail and slug bait (Metaldehyde 2.0%, Carbaryl 2.0% and Captan 0.5%) and Lamdex (Lambda-Vyhalothrin [pyrethroid] 50 g L^{-1}), applied at maize emergence. Supplementary irrigation was applied to the maize and cover crops when necessary, as summarized in Table 5.2

5.2.2 Determination of winter cover crop biomass and maize yield, nutrient concentration and uptake

Winter cover crop biomass yield were sampled as reported in section 3.2.2. Maize grain yield was taken from a net plot of 6 m × 2 m, representing the two central rows. Cover crop biomass and maize grain samples from the 4^{th} cycle (2010/11 season) were milled and sieved (< 0.1 mm), dry ashed at 450°C overnight and digested in 1 M HCl to determine total nutrient content. Phosphorus was determined using the Murphy & Riley (1962) molybdenum blue procedure (Hunter, 1974) and K, Ca, Mg, Cu, Mn, and Zn were determined by an atomic absorption spectrophotometer (AAS, AA-6300, Shimadzu, Japan). Nitrogen and carbon were determined before ashing, using near-infrared refractometer (NIR) (Eckard *et al.*, 1988). Nutrient uptake in grain was determined on a plot-by-plot basis by multiplying the nutrient concentrations by grain yield.

5.2.3 Soil sampling and analysis

Soil sampling and processing was carried out using the same procedure as described in section 3.2.3. Soil pH was measured in 1.0 M KCl (1: 2.5 soil/water ratio) using a pH meter (Model pH 330 SET-1, 82362). Electrical conductivity (EC) was analysed from a soil/water suspension after it had been allowed to settle for 1 hour using an electrical conductivity meter (Model EC Cond 330i). Calcium (Ca) and Mg were extracted from the soil by 1 M KCl and P, K, Zn, Cu, Mn by the Ambic-2 extracting solution. Phosphorus was determined using the molybdenum blue procedure (Murphy & Riley, 1962). The other elements were determined by an atomic absorption spectrophotometer (AAS, AA-6300, Shimadzu, Japan). Extractable acidity (cmol L^{-1}) was determined from the 1M KCl extract by titration using 1M NaOH. Soil inorganic N (NH_4^+ and NO_3^{2-}) was determined in freshly sampled soil (0 – 20 cm depth) before planting maize using a Skalar San Plus System (Breda, The Netherlands), after extraction with 0.5 M K_2SO_4 (1:4, soil: solution). Total soil N was determined using NIR.

5.2.4 Data Analysis

Winter cover crop dry matter yield data was pooled over four years (2007 – 2011) to included data from the 1st and 2nd years of practice (Murungu *et al.*, 2010a). Analysis of variance (ANOVA) was carried out using GenStat Release 12.1 statistical software (Lawes Agricultural Trust, 2009). Data was tested for conformity with the assumptions underlying ANOVA, including homogeneity of variance tests, before being subjected to ANOVA. Where transformation was not required and significant differences occurred, means were separated using least significant differences (LSD) at the 0.05 level of significance. Where transformation was required, back-transformed means are shown, without presentation of the LSD.

The aim of the soil analysis was to determine how oat and vetch winter cover crops as well as fertilizer application to maize affected nutrient availability at 0 – 5 and 5 – 20 cm soil depths, following four years of continuous rotation (this analysis was not concerned with determining main effect differences across seasons). The statistical analysis was therefore limited to an evaluation of the cover crop type × fertilizer × depth interaction from soil sample data collected in the 4th year (section 3.2.3).

Maize grain yield data was combined across the four maize seasons (2007 – 11) and the measurements were subjected to ANOVA as a factorial design (cover crop type × fertilizer × season) using GenStat Release 12.1 to determine yield trends under continuous practice. Treatment means for each maize season were used to calculate the N, P, K and Zn fertilizer replacement index (FRI) kg ha^{-1} on a plot-per-plot basis according to the method of Tian *et al*. (2000) as follows:

$$\textbf{FRI} = \frac{Maize\ yield\ increase\ by\ cover\ crop}{Maize\ yield\ increase\ by\ fertilizer} \times fertilizer\ rate$$

Where maize yield increase by cover crop equals:

$$\frac{Maize\ yield\ with\ cover\ crop\ only - Maize\ yield\ in\ no\ fertilizer\ control}{Maize\ yield\ with\ cover\ crop\ only};$$

and maize yield increase by fertilizer equals:

$$\frac{Maize\ yield\ with\ fertilizer\ only - Maize\ yield\ in\ no\ fertilizer\ control}{Maize\ yield\ with\ fertilizer\ only}.$$

5.3 RESULTS

5.3.1 Effects of cover crop and fertilizer on cover crop biomass and nutrient concentration

The interaction effects between winter cover crop type and fertilizer on pooled (4 years) cover crop and weed dry matter input were not significant ($p>0.05$). However, cover crop type effects were significant ($p<0.01$), with oat giving the highest (35 Mg ha^{-1}) biomass input, followed by grazing vetch (28 Mg ha^{-1}), then by weedy fallow with least (15 Mg ha^{-1}) (Fig. 5.1). The major weeds in the weedy fallow over winter were *Capsella bursa-pastoris*, *Malva parviflora*, *Sonchus oleracius* and *Stellaria media.*

Cover crop type × residual fertilizer interaction effects on winter cover crop residue and weeds nutrient concentration were not significant ($p>0.05$) except for N,Cu and the C:N ratio (Table 5.1). The interaction showed that fertilizer application had the effect of increasing the N concentration and reduced the C:N ratio of oat residues, but did not have an effect on grazing vetch and winter weeds (Table 5.1). Fertilizer application also increased Cu and N concentration of oat and weed residues but had no effect on grazing vetch (Table 5.1). Cover crop type had a significant ($p<0.05$) effect on Ca, Mg, Mn and Zn, but not on Fe, K and P concentration in the residues (Table 5.2). Grazing vetch residues had the highest concentration of Zn and significant at ($p<0.001$). Its Ca and Mg concentrations were also higher than those of oat but similar to weedy fallow (Table 5.2). Fe and Mn concentrations were similar for oat and grazing vetch but their concentration in both was lower than that obtained for weedy fallow (Table 5.2). Fertilizer application significantly ($p<0.05$) effect of increased Mn concentration, but had no effects on Ca, K, Mg, P and Zn concentration (Table 5.2).

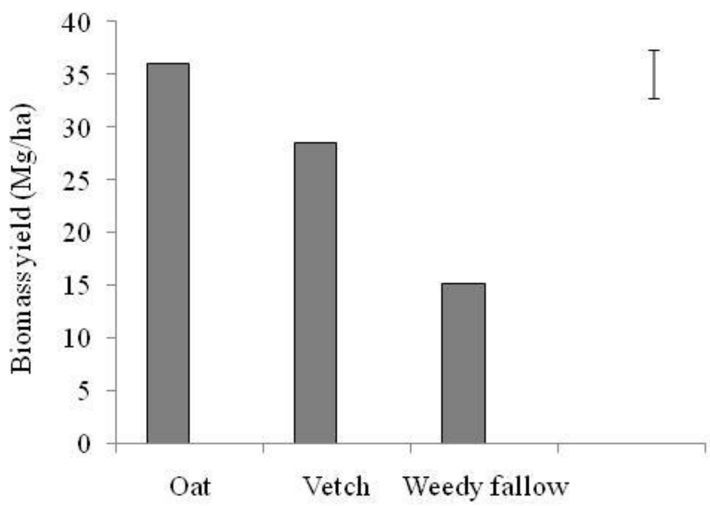


Figure 5.1 Dry matter input from oat, grazing vetch and weedy fallow treatments, pooled over four years (2007 – 2011). Error bar represents the LSD at $p<0.05$

Table 5.1 Cover crop type × residual fertilizer interaction effects on Cu, N and the C: N ratio of above ground winter cover crop and weed residues

		Cu (mg kg^{-1})	**N** (%)	**C : N ratio**
Oat	Fertilized	4.49 d	3.24 b	13.59 c
	Non fertilized	1.51 e	1.86 c	25.95 a
Grazing vetch	Fertilized	6.67 c	4.12 a	10.96 c
	Non Fertilized	6.55 c	4.14 a	10.62 c
Weedy Fallow	Fertilized	10.53 a	2.44 bc	16.97 b
	Non fertilized	8.56 b	2.53 bc	13.82 bc
***P* value**		*	*	***
Cv%		10.7	13.8	10.9

Means followed by the same letter are not significant. *, **, *** = significant at $p<0.05$, 0.01 and 0.001 respectively

5.3.2 Effects of cover crop type and fertilizer on soil mineral N and total N

The cover crop type × fertilizer interaction had a significant effect on ammonium-N and total mineral N (NH_4-N + NO_3-N), but its effect on nitrate-N was not significant. Fertilizer application increased ammonium-N by 17.1 mg kg^{-1} and total mineral N by 19.6 mg kg^{-1} on the grazing vetch rotation but not on the oat or weedy fallow (Table 5.3). Cover crop type had a significant ($p<0.05$) effect on nitrate-N with grazing vetch giving the highest nitrate (7.49 mg kg^{-1}) whilst oat (5.28 mg kg^{-1}) was not significantly different from the weedy fallow (4.51 mg kg^{-1}). All factors and interactions had no significant ($p>0.05$) effect on total soil N (Appendix 5) as measured using NIR.

Table 5.2 Effects of cover crop type and fertilizer on cover crop Ca, Mg, Mn, P, K, Zn and Fe concentration in above ground residues

	Ca	Mg	P	K	Zn	Fe	Mn
	(%)				(mg kg^{-1})		
Cover crop type							
Oat	0.230 b	0.1615 b	0.351	2.788	28.8 a	248 b	49.0 b
Grazing vetch	0.933 a	0.3341 a	0.445	2.984	84.6 b	366 b	50.0 b
Weedy fallow	0.897 a	0.2845 a	0.378	2.941	33.9 a	791 a	66.4 a
P value	***	***	n.s	n.s	***	**	*
Fertilizer							
Fertilized	0.724	0.2703	0.421	3.038	54.8	534	62.0
Non fertilized	0.649	0.2498	0.362	2.771	43.5	403	48.2
P value	n.s	n.s	n.s	n.s	n.s	n.s	*
Cv%	25.1	16.3	22.5	12.9	32.0	43.5	19.3

Means followed by the same letter are not significantly
n.s = not significant *, **, *** = significant at p<0.05, 0.01 and 0.001 respectively

Table 5.3 Winter cover crop type × fertilizer interaction effects on soil mineral N (mg kg^{-1})

		Oat	Grazing vetch	Weedy Fallow	$LSD_{(0.05)}$	Cv%
Ammonium-N	Fertilized	42.6	60.9	43.8	8.60**	10.3
	Non fertilized	42.1	40.4	41.4		
Total mineral N	Fertilized	49.3	68.7	49.1	8.99**	9.5
(NH_4-N and NO_3-N)	Non Fertilized	46.0	47.6	45.1		

** = significant at p<0.01

5.3.3 Effects of cover crop type and fertilizer on soil extractable P, bases and micronutrients

Cover crop type × fertilizer × soil depth interactions were not significant ($p>0.05$) for all the extractable nutrients that were analyzed. However, cover crop type effects were significant on P ($p<0.001$), Mg, Cu and Mn ($p<0.01$), and Zn ($p<0.001$) but not on Ca and K. The winter cover crops gave higher values for P, Cu and Zn than the weedy fallow (Table 5.4). Grazing vetch gave lower values for Mg than oat and weedy fallow. Phosphorus and Mn were highest on the grazing vetch and lowest on the weedy fallow. Extractable Mn content under oat was similar to that of the weedy fallow (Table 5.4). Fertilizer had a significant effect on Mg ($p<0.01$), P ($p<0.05$), and Zn, but had no effect on Ca, Cu, Mn and K. The fertilized rotations gave higher P and Zn, but lower Mg than the non fertilized (Table 5.4). There were also significantly higher amounts of Mn ($p<0.01$), K ($p<0.001$) and Zn at 0 – 5 cm than at 5 – 20 cm (Table 5.4).

5.3.4 Effects of cover crop type and fertilizer on soil pH, EC and extractable acidity

Interaction effects of cover crop type, fertilizer and soil depth on soil EC and pH were not significant ($p>0.05$), except for the cover crop type × soil depth interaction effect on EC (Fig. 5.2). The oat treatment had higher EC at 0 – 5 cm than at 5 – 20 cm. However, in the grazing vetch and weedy fallow (control) treatments, the EC levels were not different between the two depths (Fig. 5.2). Cover crop effect on pH was significant ($p<0.01$), and grazing vetch resulted in slightly lower pH (5.16) than the weedy fallow (5.41), which was similar to oat (5.38 ± 0.211). Fertilizer effects on pH were also significant ($p<0.01$), as the fertilized plots gave slightly lower pH (5.26) than unfertilized plots (5.37 ± 0.08) (see Appendix 5). The pH in the grazing vetch plots was similar to that in the fertilized treatments.

Table 5.4 Effects of cover crop type, fertilizer and depth on extractable nutrients (mg L^{-1})

	Ca	**Mg**	**P**	**K**	**Cu**	**Mn**	**Zn**
Cover crop type							
Oat	1329	389.9 a	30.9 b	112.4	4.62 a	25.2 b	6.38 a
Grazing vetch	1347	330.4 b	39.9 a	118.7	4.36 a	31.8 a	7.05 a
Weedy fallow	1397	376.7 a	19.8 c	102.2	3.96 b	22.6 b	4.40 b
P value	n.s	**	***	n.s	**	**	***
Fertilizer							
Fertilized	1319	341.8	32.5	113.3	4.27	27.0	6.53
Non fertilized	1396	368.8	27.9	108.9	4.35	26.8	5.35
P value	n.s	**	*	n.s	n.s	n.s	*
Depth							
0 – 5 cm	1370	365.1	32.1	139.4	4.28	30.9	6.77
5 – 20 cm	1345	345.5	28.2	82.8	4.35	22.9	5.96
P value	n.s	n.s	n.s	***	n.s	**	**
Cv%	14.9	11.9	31.8	30.6	15.7	31.4	37.2

Means followed by the same letter are not significantly different ($p>0.05$).

n.s = not significant *, **, *** = significant at $p<0.05$, 0.01 and 0.001 respectively

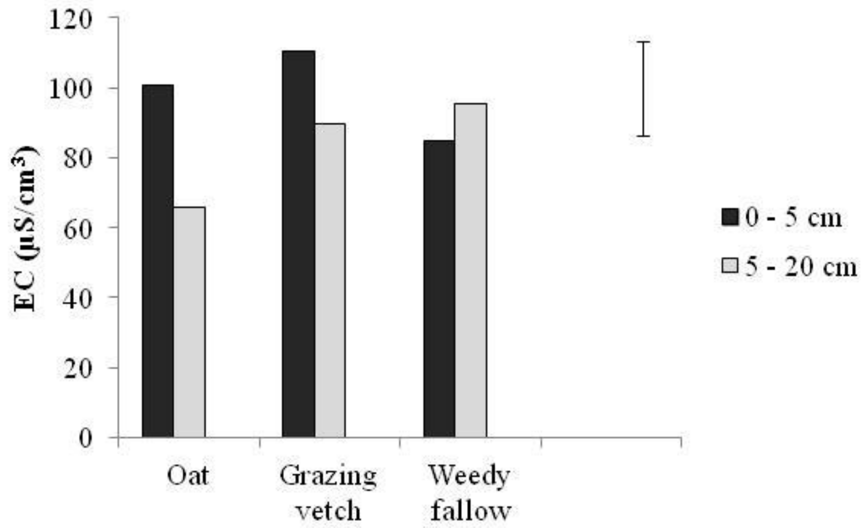


Figure 5.2 Cover crop type × depth interaction effect on soil electrical conductivity (EC)

5.3.5 Effects of cover crop type and fertilizer on maize grain yield, nutrient content and uptake

The cover crop type × fertilizer × season interaction effect on maize yield was significant ($P<0.001$). Regardless of fertilizer application, maize yields were significantly increased in the grazing vetch rotations in the 2nd season (Fig. 5.3). The weedy fallow gave the lowest maize yield in the 1st season. However, this was similar to the yield under oat in the 2nd, 3rd and 4th seasons without fertilizer application. In the fertilized system, the winter cover crops gave higher maize yield than the weedy fallow from the 3rd to the 4th season. The maize yield trend in Fig. 5.3 shows a continuous dip from the 2nd season onwards, particularly for the weedy fallow and all unfertilized treatments. Figure 5.4 shows the yield benefits from the winter cover crops in terms of percentage increase in grain yield. In the non-fertilized systems, grazing vetch gave significantly higher maize yield than oat from the 2nd season onwards as well as % maize grain yield benefit of up to 1100% in the 3rd year when compared with the weedy fallow (Fig. 5.4).

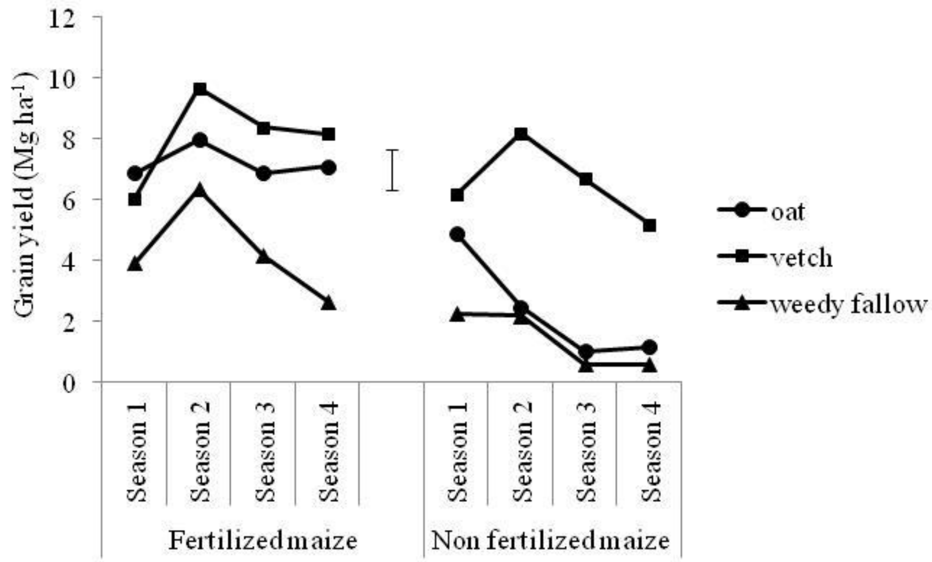


Figure 5.3 Effects of cover crop type and fertilizer regime on maize yield across four seasons (2008 – 11).

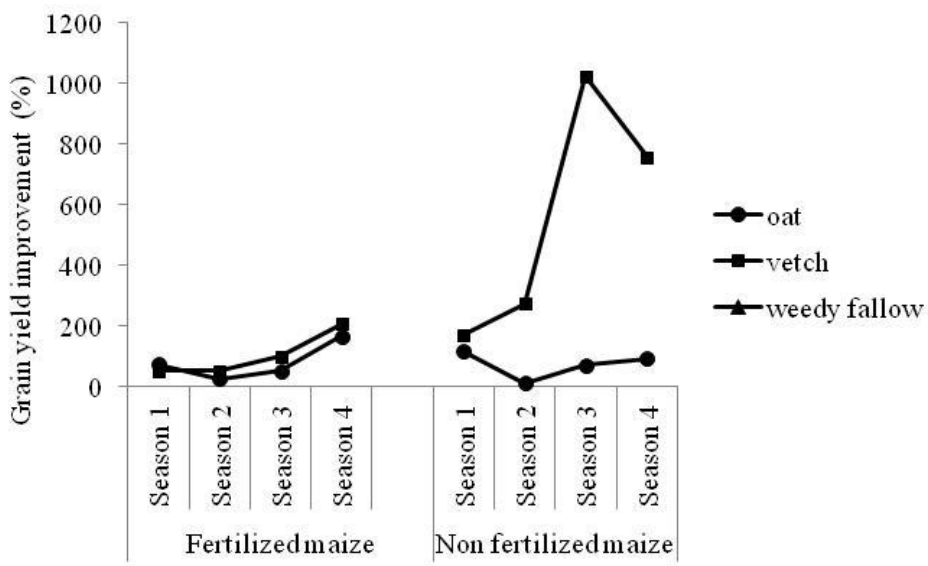


Figure 5.4 Maize yield improvement by oat ang grazing vetch winter cover crops over a four year period

Cover crop type × fertilizer regime interaction had no significant effect on content of all other nutrients in grain yield except for N. While fertilized oat, grazing vetch and weedy fallow plots gave similar grain N content (Fig. 5.4), a lack of fertilizer application reduced maize grain N content on the oat and weedy fallow but not in the grazing vetch treatment (Fig. 5.4). Cover crop type effects were also not significant ($p>0.05$) on all grain nutrient parameters. Fertilizer application, however, increased Ca and Cu ($p<0.05$) in the grain, but reduced Mg content regardless of cover crop type (Table 5.5).

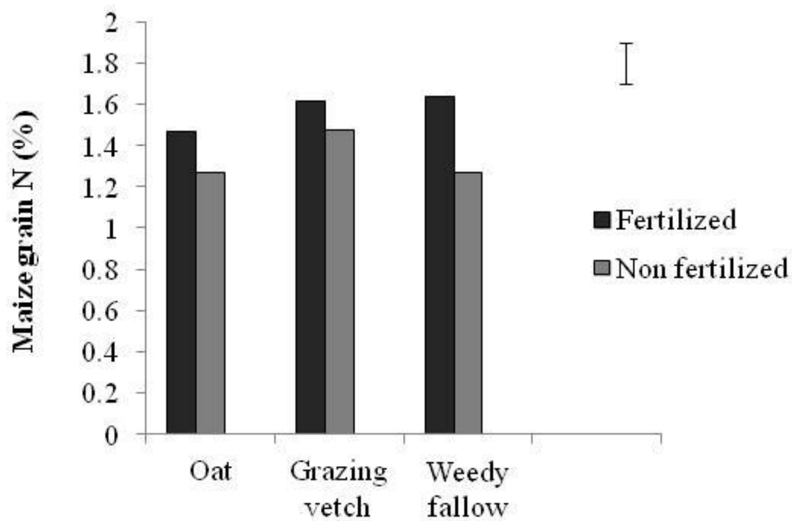


Figure 5.5 Winter cover crop type × fertilizer interaction effects on grain N concentration

Table 5.5 Effects of fertilizer on grain nutrient concentration

	Ca	Mg	P	K	Zn	Na	Cu	Mn
	(%)				(mg kg^{-1})			
Fertilized	0.0085	0.10	0.287	0.318	25.0	26.2	1.748	8.36
Non fertilized	0.0058	0.112	0.307	0.305	27.2	24.4	1.113	8.42
P value	*	*	n.s	n.s	n.s	n.s	**	n.s
Cv%	25.2	8.4	8.8	10.3	20.9	27.8	27.5	15.6

Means followed by the same letter are not significantly different

n.s = not significant *, **, *** = significant at p<0.05, 0.01 and 0.001 respectively

Table 5.6 Interaction effects of winter cover crop type and fertilizer application to maize on nutrient uptake/accumulation in grain (kg ha^{-1}) during the 4th year of continuous maize-winter cover crop rotation

	Grazing vetch		**Oat**		**Weedy fallow**		**LSD$_{(0.05)}$**	**Interaction**
	Fertilized	No fertilizer	Fertilized	No fertilizer	Fertilized	No fertilizer		***P* value**
Nitrogen (kg ha^{-1})	131.4	78.1	90.2	19.2	30.9	11.3	27.29	*
cv (%)			-------------------- 23.5 --------------------					
Phosphorus (kg ha^{-1})	23.05	16.96	19.6	3.69	8.02	1.83	5.56	*
cv (%)			-------------------- 23.6 --------------------					
Potassium (kg ha^{-1})	24.55	17.58	22.22	3.57	9.04	1.76	5.51	*
cv (%)			-------------------- 21.8 --------------------					
Magnesium (kg ha^{-1})	7.92	6.14	7.05	1.40	2.75	0.67	2.08	*
cv (%)			-------------------- 25 --------------------					
Zinc (g ha^{-1})	179.8	145.7	161.2	30.1	79.4	18.0	22.15	***
cv (%)			--------------------11.2 --------------------					
Copper (g ha^{-1})	16.82	4.94	9.52	1.28	4.86	0.76	3.77	*
cv (%)			-------------------- 30.8 --------------------					
Manganese (g ha^{-1})	63.4	44.6	55.2	13.6	25.2	2.7	10.68	*
cv (%)			-------------------- 16.2 --------------------					

*, *** = significant at p<0.05 and 0.001 respectively

The effect of winter cover crop type × fertilizer interaction on uptake of N, P, K, Mg, Zn, Mn and Cu uptake was significant ($p<0.05$) (Table 5.6). However, for Ca, there was no effect. While uptake of all nutrients in fertilized maize grain was generally the same for oat and grazing vetch rotations, non-fertilization of maize reduced nutrient uptake under oat when compared to grazing vetch. The lowest uptake for all nutrients was obtained from non fertilized maize under the weedy fallow treatment but was not significantly different from non fertilized maize under oat (Table 5.6). Calcium uptake was however, lowest in the non-fertilized treatments regardless of cover crop type.

5.3.6 Fertilizer replacement indices of the winter cover crops

The fertilizer replacement indices of the grazing vetch and oat winter cover crops for N, P, K and Zn over the four seasons are presented in Table 5.7. Grazing vetch generally gave higher fertilizer replacement values than oat for all nutrients.

Table 5.7 Fertilizer replacement value of grazing vetch and oat cover crops over four maize seasons (2008 – 11)

	Grazing vetch				Oat			
	N	P	K	Zn	N	P	K	Zn
	(kg ha^{-1})							
Season 1	89.4	44.7	59.6	2.23	76.3	38.1	50.9	1.91
Season 2	68.7	34.4	45.8	1.72	10	5	6.6	0.25
Season 3	63.8	31.9	42.5	1.6	29.3	14.7	19.5	0.73
Season 4	69.2	34.6	46.13	1.73	37.5	18.8	25	0.94
Total	291.1	145.6	194.03	7.28	153.1	76.6	102	3.83

5.4 DISCUSSION

There is abundant literature showing that yield of non leguminous crops are often increased when they are grown following legumes. Similarly, our findings showed that there was greater yield response to maize following vetch than oat, especially when no fertilizer was applied. Vetch is reported to reduce the optimum N application rates for maize production due to high nitrogen replacement values of 80 – 200 kg ha^{-1} in sub tropical climates as a result of N fixation (McVay *et al.*, 1989; Utomo *et al.*, 1990; Decker *et al.*, 1994). In addition to N and P benefits as observed in the current study, grazing vetch can also provide yield improvements due to a ‘rotation effect’, which can include breaking of pest and disease cycles. Based on maize yield improvement, grazing vetch had higher fertilizer replacement values than oat (Table 5.7) and it appears that by mere inclusion of grazing vetch in maize based rotations, resource poor smallholder farmers in the EC can increase maize yield and save a total of 291.1, 145.6, 194 and 7.28 kg ha^{-1} of N, P, K and Zn fertilizer respectively over a four year period, assuming that management will be similar to that employed in this study.

Our findings with grazing vetch are in agreement with other researchers. For example, Liu *et al.* (1989) similarly reported that inclusion of N_2 fixing legumes in rotations can cause drops in pH, most likely due to rapid mineralization and subsequent nitrification of N in the legume residues. Nitrification of 1 mole of NH_4^+ produces 2 moles of H^+, thus increasing acidity. Suboptimal pH conditions can either reduce availability of some essential nutrients or increase that of others to toxic levels. Small changes in pH as observed with grazing vetch in the current study may be associated with large liming requirements for pH correction (Brady & Weil, 2008). The development of acidification in the 0 – 20 cm soil layer under vetch cover crops can however be ameliorated by lime additions. Incorporation of the lime should not be an issue of particular concern in CA systems, as recent evidence indicates that lime is effective to a depth of 60 cm in 3 years under no till (Caires *et al.,* 2005).

Grazing vetch gave higher extractable Mn than either oat or weed fallow (Table 5.4). This is in agreement with Bromfield (1958), who found that the root exudates of vetch (*Vicia sativa* L.) had pH 5.1 and were more effective in rendering Mn available, compared to root exudates of oats (*Avena sterilis* L.), which had pH 7.1. The observed Mn results could therefore be related to pH modification by the root systems of the cover crops and decomposition of the residues of their above ground biomass, as supported by the soil pH results. Both oat and grazing vetch gave slightly higher amounts of P, Zn and Cu than weedy fallows (Table 3.6) and there are several plausible explanations for this observation. Firstly, organic carbon derived from several cover crop species including vetch residues can reduce the rate of P sorption, thus increasing P availability (Ohno & Crannell 1996; Ohno & Erich 1997). Secondly, buildup of organic matter from the winter cover crops (Chapter 3) is known to favour Zn accumulation, probably by chelating of inorganic sources and formation of soluble complexes (Takkar & Walker, 1993; Rahman *et al.,* 1996). Organic matter itself is a source of Zn, P and Cu. The increase in Zn, P and Cu availability under the winter cover crops can be partly credited to winter cover crop roots bringing the nutrients from subsoils to the soil surface and by surface decomposition of above ground biomass which releases nutrients.

It is noted that P and Zn are antagonistic elements in nature, and Zn availability is reduced when available P levels in the soil are high or P fertilizer is added (Olsen, 1972). Phosphorus is thought to precipitate Zn either in the soil or at the root-soil interface. In our study, the simultaneous increase in P and Zn availability in the soil was possible perhaps because the P was added as a compound fertilizer (NPK + Zn), and the negative effects of increased P availability were counteracted by Zn additions from the compound fertilize, as supported by the significant fertilizer effects on P and Zn. Extractable P values in all treatments from this study fell in the 19 – 40 ppm range (Table 5.4), which lies within ‘medium’ availability range of 50 – 15 ppm for Bray 4-P (Olsen & Dean, 1965) For Zn, they lie within the low availability range of (< 7.5 ppm). Maize is generally more sensitive to Zn deficiency than any other micro-nutrient, including Mn and Cu (Mortvedt, undated).

Mineral nutrients and organic matter tend to accumulate in soil surface strata under zero-till regimes, due to decomposition of residues on the soil surface (Franzluebbers & Hons 1996; Howard *et al.,* 1999). Winter cover crops and maize crop residues returned to the soil surface annually, including the surface applied fertilizer were possibly the major source of increased K, Zn and EC as observed at 0 – 5 cm than at 5 – 20 cm soil depth. Grazing vetch, being a tap rooted species, maybe better able to mine nutrients from deeper horizons, and increase nutrient availability as well as SOM in the surface soil. Grazing vetch generally had higher tissue concentration of Cu, N, Ca, Mg and Zn than oat and was more effective at increasing extractable P and Mn (Table 5.4). Higher grain yield response to grazing vetch than oat may be credited to these differences in nutrient availability in these treatments.

The non-significance of all treatment and interaction effects on extractable Ca and K could be due to high inherent total contents of these elements in the relatively young soil that was used. According to Landon (1984), indices of plant available Ca are of little value, since the availability varies enormously from soil to soil and is highly dependent on a number of other factors. Calcium deficiency is generally uncommon and mostly limited to highly leached and acidic (pH < 5.5) soils. According to Mengel & Busch (1982), exchangeable K values are of limited value for predicting crop response to K since they give no direct indication of the capacity of the soil to release currently unavailable K. Values of total K may be more useful in this respect. Total N content of the soil was also not significantly affected by the treatments; N levels are inherently part of total organic carbon which has low sensitivity to changes in soil management.

When no fertilizer was applied, grazing vetch had an effect of increasing grain N content and grain yield. This implies higher protein content and improved nutritional benefits for resource poor farmers who cannot afford fertilizer. These results however differ from other published data that show a negative association of grain yield and N concentration in the grain (Greenwood, 1982). This negative association occurs only when soil N is not limiting, which was not the case in this study. Reduced Mg concentration in the grain of fertilized maize may have been caused by increased competition between NH_4^+ ions (from the fertilizer) and Mg for uptake in the soil. According to Halvin *et al.* (1999), absorption of NH_4^+ by roots reduces Mg uptake. Exchangeable Mg levels of > 60 mg L^{-1} are considered sufficient for uptake (Landon, 1984) and the range obtained in this study was 300 – 400 mg L^{-1} (Table 5.4) It is suspected that the large amounts of Ca, K and NH_4^+ arising from basal and top dressing fertilizers (Lime of ammonium nitrate) and vetch residues, respectively, against the relatively low amounts of total Mg in the soil, might have decreased Mg uptake by the maize as a result of competition with NH_4^+ ions uptake by maize

5.5 CONCLUSIONS

The practice of winter cover cropping can significantly increase the availability and uptake of some essential plant nutrients and maize yield in low fertilizer input maize-based CA systems as found in the EC. However, effects are dependent on winter cover crop type and fertilizer application.. The winter cover crops made a contribution on the fertility of N, P and Zn, which are major limiting nutrients in South African soils. For resource poor farmers who cannot afford mineral fertilizers, grazing vetch appears more ideal as it will significantly improve maize yield and has a high fertilizer replacement value. Future studies need to test these technologies under rain-fed conditions of the EC and in vegetable production systems where they could make a major contribution.

6 WINTER COVER CROPS AND NITROGEN FERTILIZER EFFECTS ON AGRONOMIC PERFORMANCE AND PROFITABILITY OF MAIZE

Abstract

A field experiment was conducted to study the effects of winter cover crops and nitrogen (N) management on agronomic performance and profitability of maize under conservation agriculture (CA) and irrigation. The treatments were factorial combinations of winter cover crops namely oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) with five N fertilization rates (0, 60, 120, 180 and 240 kg ha^{-1}). Grazing vetch generally gave higher mean grain yield than oat, which was similar to weedy fallow. The highest partial factor productivity (P*f*P) indices for grazing vetch and oat (64.4 and 44.1 ± 5.9 kg grain kg^{-1} N applied respectively) were obtained at 60 kg N ha^{-1} for both cover crops. Where no N fertilizer was applied, grazing vetch gave maize yields of 4.71 and 7.26 Mg ha^{-1} in the 1st and 2nd seasons, translating into N fertilizer replacement (NFR) values of 120 and 60 kg N ha^{-1} respectively. There was no significant ($p>0.05$) difference in maize grain yield between oat and weedy fallow hence oat was given a NFR value of 0 kg N ha^{-1}. In the two maize seasons, the highest net benefits were obtained at 180 kg ha^{-1} for both oat and grazing vetch. The TVC were highest on the grazing vetch due to the cost of grazing vetch seed. The highest MRR (622%) was obtained grazing vetch with an N fertilizer application rate of 120 kg ha^{-1}. In the 2nd season, the highest MRR of 1306% was obtained from the grazing vetch with no N fertilizer treatment. It appears that grazing vetch can produce enough maize yield response to pay its way in the maize-based system. No additional N may be required to counter possible N immobilization by oat residues.

Keywords: Conservation agriculture; grazing vetch; nitrogen fertilizer replacement; oat

6.1 INTRODUCTION

Low nitrogen (N) application rate is among the main causes of low maize grain yield (< 3 Mg ha^{-1}) in irrigated smallholder farmer systems of the Eastern Cape (EC) (Bembridge, 2000; Monde *et al.,* 2005; Fanadzo *et al.,* 2010). Nitrogen rates can be as high as 220 kg ha^{-1} for maize yield potentials greater than 12 Mg ha^{-1} under irrigation in the EC (FSSA, 2007). However, farmers use low quantities of N fertilizer (< 60 kg N ha^{-1}) due to lack of capital (Monde *et al.,* 2005; Fanadzo, 2010). Agronomic interventions that increase nitrogen use efficiency (NUE) may improve maize yields and at least economic performance in the smallholder systems. Nitrogen use efficiency (NUE) can be defined as the yield of grain per unit of available N in the soil (Moll *et al.*, 1982).

Recent interest in conservation agriculture (CA) necessitated research into cover crops for soil erosion control, nutrient leaching reduction, soil organic matter (SOM) restoration and weed suppression in maize based systems of the EC. Whilst leguminous winter cover crop species such as grazing vetch appeared ideal as an N source because of their ability to fix N in low N soil, grasses such as oat are also interesting because their wide C:N ratio means slow decomposition and covering of the soil for longer and thus protecting the soil against erosion. Additionally, their dense rooting pattern means better protection of sandy soils against erosion and nutrient leaching. Research work carried out elsewhere shows that legume residues in rotations generally improve N availability whilst grass residues can immobilize it (Clark, 2007). The magnitude of the effect is however dependant primarily on cover crop residue quality and synchronization of the N release with N demand of the associated crop (Myers *et al.,* 1994).

Maize yield response to N fertilization is primarily a function of soil characteristics (depth, drainage, SOM) and the yield potential of the environment (FSSA, 2007). It is also influenced by the presence of crop residues (Randall & Bandel, 1991; Archer *et al.*, 2008). Information on maize yield response to N fertilizer under oat and grazing vetch winter cover crops is required for better management of N fertilizer under these cover crops in order to optimize maize yield and maximize economic benefits from CA practice in maize-based smallholder systems of the EC. Results in Chapter 5 suggested that grazing vetch and fertilized oat cover crops increase soil mineral N, P and Zn and their uptake by maize give better yields. It would be essential to understand what happens to these effects with increasing rates of fertilizer, particularly N.

Various indices are used in agronomic research to assess NUE, either based on using ^{15}N-labeled fertilizers to estimate recovery of N (Doberman, 2007) or differences between fertilized plots and unfertilized control ('difference method'). The difference method is simple and cost effective, making it partially suitable for situations where resources are limited (Doberman, 2007). Nitrogen difference indices include partial factor productivity (P*f*P) defined as crop yield per unit of N applied, agronomic efficiency (AE) of applied N defined as unit yield increase per unit applied N (Doberman, 2007). The P*f*P is an aggregate efficiency index that includes contributions to crop yield derived from uptake of indigenous soil N and applied N resources, as well as the efficiency with which N acquired by the plant is converted to grain yield (Doberman, 2007).

Marginal analysis can be used for calculating the marginal rate of return (MRR) between technologies, proceeding in a stepwise manner from a lower-cost technology to the next higher-cost technology, and comparing MRR to acceptable minimum rates of return (Perrin *et al.*, 1988). The procedure may thus be useful for determining the economic benefits of fertilizer application after having invested in winter cover crops, as well as determining the amount of fertilizer that will give the highest returns for maize grown after oat and grazing vetch winter cover crops. Considering these aspects, the objective of this study was to determine maize yield response to N fertilizer, NUE and profitability of maize at different N fertilization rates following oat and grazing vetch winter cover crops.

6.2 MATERIALS AND METHODS

6.2.1 Experimental site, design and layout

The study was carried out at the University of Fort Hare research farm as a separate experiment in a field adjacent to the four year old field experiment reported in Chapters 3, 4 and 5. The location and climate of this research site has been described previously (Section 3.2). The elemental content of the soil was presented in Table 3.1. The soil type and the climate closely resemble that of smallholder irrigators in the EC. Prior to this study, the land had been under conventional tillage with maize crop.

At the beginning of the trial (2009), white oat (*Avena sativa* cv. Serderberg) and grazing vetch (*Vicia darsycapa* cv. Max) were planted by hoe on the 1st of June without tillage or fertilizer on 30 m × 6 m plots. A control plot was included where no cover crops were grown and weeds were left to grow. The treatments were laid in a randomized complete block design (RCBD) with three replications. Grazing vetch was inoculated with *Rhizobium legunominosarium* biovar *viciae* having 5×10^8 rhizobial cells g^{-1} (Stimuplant CC, Zwavelpoort 0036, SA) at planting. The cover crops were sown at seed rates of 90 kg ha^{-1} for oat and 35 kg ha^{-1} for grazing vetch. No weed or pest control was done during the growth of the cover crops. Supplementary overhead irrigation water was applied to all treatments when necessary as summarized in Table 6.1. All plots received similar amounts of irrigation.

All cover crops were terminated in mid October by rolling them and applying glyphosate (360 g L^{-1}) at a rate of 5 L ha^{-1}. Rolling was done to allow glyphosate to reach any weeds growing in the understory. At this stage cover crops had reached the flowering stage or just starting the grain filling period and no grain yield was harvested from them. Six weeks later, all plots, including control plots, were split into five plots of gross size 5 m × 6 m. Maize cultivar PAN 6479 was over-seeded initially and later thinned to attain a plant population of 37 000 plants ha^{-1} at 15 days after emergence (DAE). The maize was planted using jab planters and no tillage was done. A basal fertilizer of single super phosphate (SSP [20% P_2O_5]) + potassium sulphate (50% K) was applied into all planting holes at 40 kg ha^{-1} and 60 kg^{-1} ha, respectively.

Table 6.1 Rainfall and irrigation water (mm) received during periods of summer maize and cover crops growth (2009 -2011)

Month	2009/10		2010/11	
	Rainfall	Irrigation	Rainfall	Irrigation
Jun	20.5	20	48.3	30
Jul	53	10	16.8	45
Aug	15	40	12	60
Sept	25.3	20	9.1	0
Oct	56.4	30	65.7	15
Nov	50.8	20	62.3	40
Dec	42.5	40	122.6	15
Jan	103.2	0	103.2	15
Feb	40.2	40	40.2	30

Nitrogen fertilizer was applied at five levels (0, 60, 120, 180 and 240 kg ha^{-1}) into the split plots as lime of ammonium nitrate LAN (28% N). The N fertilizer was split applied, with a third applied at planting and the rest applied at 6 weeks after crop emergence (WACE). This gave a split plot design, where the main plot factor was winter cover crop type while the sub plot factor was N fertilizer rate. Weeds in the maize crop were controlled using Basagran 44% (3-[1-methylethyl]-1*H*-2,1,3-benzothiadiazin-4[3H]-one 2,2-dioxide) sprayed 2 WACE at the rate of 2 L ha^{-1} combined with hand pulling throughout maize growth, such that the crop was kept weed free. Maize stalk borer (*Busseola fusca*) was controlled with Dursban (chloropyrifos) applied at a rate of 2 L ha^{-1} in the whorl at about 9 WACE. After maize grain harvest, maize stalks were rolled, glyphosate applied like in the previous cover crops. Cover crops were planted as in the first season on the 1st of June 2010.

6.2.2 Winter cover crops biomass sampling and analysis

In order to determine cover crop and weed dry weights at the period of cover crop termination (28th October 2009), two quadrants measuring 35 cm × 35 cm were randomly placed in each plot and plant biomass was destructively sampled by cutting at the soil surface. Weeds and cover crops were separated and oven dried to a constant weight at 65°C and dry weight determined. Cover crop and weed samples were ground and sieved (< 1 mm). The C and N contents were determined using the LECO CNS autoanalyzer.

6.2.3 Maize growth and yield measurements

Chlorophyll content was measured using a chlorophyll (SPAD) meter (Konica Minolta model SPAD-502). There is a strong positive relationship between SPAD values and maize N status (Bullock & Anderson, 1998; Vetsch & Randall, 2004). The SPAD readings were obtained from the youngest fully extended leaves (Sims *et al.*, 1998) of six randomly selected maize plants inside the net plot at 2, 4, 6 and 8 WACE. Maximum plant height was measured at grain physiological maturity from six randomly selected plants from two central rows and averaged. A net plot of 3 m × 2 m consisting of three middle rows provided data on grain and stover yields. Samples were oven dried to a constant weight at 65°C and dry weight determined. Grain samples were ground and sieved (< 1 mm) and the N concentration of the grain was determined using the LECO CNS autoanaylzer.

6.2.4 Soil mineral N

Six random soil samples were taken from each plot at a depth of 0 – 20 cm using a 7 cm diameter auger to determine soil mineral N status at maize planting. When taking soil samples, plant residues at the surface were carefully removed. The mineral N was determined in freshly sampled soil by extraction with 0.5 M K_2SO_4 (1:4, soil: solution) and analyzed colorimetricaly as described by Okalebo *et al.* (2002).

6.2.5 Nitrogen fertilizer use efficiency indices

The agronomic efficiency (AE) and the partial factor productivity (P*f*P) were calculated according to Dobermann (2007) as follows:

$$\mathrm{AE}\ (\mathrm{kg\ grain\ kg^{-1}N\ applied}) = (\mathrm{Y} - \mathrm{Y_0})/\mathrm{F}$$

$$\mathrm{P}f\mathrm{P}\ \ (\mathrm{kg\ grain\ kg^{-1}N\ applied}) = \mathrm{Y}/\mathrm{Y_0}$$

Where:

F = amount of (fertilizer) N applied (kg ha^{-1})

Y = maize grain yield with applied N (kg ha^{-1})

Y_0 = maize grain yield (kg ha^{-1}) in a control treatment with no N

6.2.6 Data analyses

Cover crop dry weight, maize grain yield and soil mineral N data was subjected to an analysis of variance (ANOVA) using GenStat Release 12.1 (Lawes Agricultural Trust, 2009). Data was tested for conformity to the assumptions underlying ANOVA, including homogeneity of variance tests before being subjected to ANOVA. Where transformation was not required and significant differences occurred, means were separated using least significant differences (LSD) at the 0.05 level of significance. Where transformation was required, back-transformed means are shown, without presentation of the LSD. Maize yield response to N fertilizer rate on the no cover crop (control) was used to estimate the N fertilizer replacement value of grazing vetch and oat winter cover crops. The response to N fertilizer was evaluated using linear and quadratic trends from single degree of freedom comparisons. Whenever trends were significant, regression equations were calculated and relavant graphs were obtained.

Treatments were subjected to a marginal analysis to determine the treatment combination that would give the highest return to farmers (CIMMYT, 1988). This was done using the current market price for inputs at planting and for maize grain (R1750.00 ton^{-1}). The gross benefit was the product of field price of maize grain and the yield for each treatment. The total variable costs (TVC) were limited to cover crop seed, labour and N fertilizer costs. The net benefit (NB) per ha for each treatment was the difference between the gross benefit and the TVC.

After the net benefits were determined, a dominance analysis was conducted (CIMMYT, 1988) and dominated treatments were excluded from further analysis. Marginal rate of return (MRR) was calculated for each increase in N fertilizer rate. The MRR between any pair of treatments denotes the return per unit of investment in fertilizer expressed as a percentage. MRR between fertilizer rates for each winter cover crop type was calculated using the following formula:

$$\frac{\text{change in net benefit (NB2} - \text{NB1)}}{\text{change in TVC (TVC2} - \text{TVC1)}} \times 100$$

Thus, a MRR of 150% in switching from fertilizer rate 1 to fertilizer rate 2 implies that for each R1.00 invested in fertilizer, the farmer can expect to recover R1.00 plus an additional return of R1.50. Minimum acceptable rate of rate (MARR) is the return on investment that is assumed can make farmers to voluntarily switch to a proposed new technology and it is generally given as 50 - 100% (Perrin *et al.,* 1988). The most profitable rate of fertilizer N under each cover crop type was assumed to be the N fertilizer rate giving the highest MRR, but above the MARR.

6.3 RESULTS

6.3.1 Effects of cover crop type on cover crop dry weight, N and C plant content and soil mineral N at planting maize in the 1st season (2009/10)

There were significant ($p<0.01$) differences in biomass yields and N contents of residues between oat, grazing vetch and winter weeds. Grazing vetch gave the highest biomass yields (4.62 ± 0.12 Mg ha^{-1}), followed by oat (3.53 Mg ha^{-1}) and weedy fallow (1.2 ± 0.12 Mg ha^{-1}). Grazing vetch residues had the highest N content (4.37%), followed by weedy fallow residues (3.37%) and lastly oat (1.48%). The major weed species infesting the weedy fallow during the winter were *Capsella bursa-pastoris, Sonchus oleracius* and *Stellaria media.* There were no significant differences ($p>0.05$) in C content of the cover crops residues. However, C:N ratios were significantly different ($p<0.05$) where grazing vetch had the lowest C:N ratio (9.8) and oat the highest (28.3). There were no significant differences in nitrate-N, ammonium-N or total mineral N in the soil at planting maize between grazing vetch, oat and the weedy fallow plots (see Appendix 6).

6.3.2 Effects of cover crop type and N fertilizer rate on maize growth; yield and N use efficiency in 1st season (2009/10)

4.4.1.1 Leaf N as estimated using the SPAD meter

The cover crop type × fertilizer rate interaction effect on leaf N was not significant ($p>0.05$). Cover crop type effects were however significant at 2, 4 and 6 WACE. As shown in Table

6.2, grazing vetch gave higher SPAD readings than oat and weedy fallow during this period. Fertilizer effects were significant at 4, 6 and 8 WACE (Fig. 6.1). SPAD values were lowest for 0 kg N ha^{-1} and generally increased with increasing fertilizer rate up to 240 kg ha^{-1}, except at 8 WACE, when there were no significant differences between 120 and 180 kg N ha^{-1} (Fig. 6.1).

Table 6.2 Effects of cover crop type on SPAD meter readings at 2, 4, 6 and 8 weeks after crop emergence (WACE)

	2WACE	4WACE	6WACE	8WACE
Weedy fallow	34.99	42.65	42.05	47.47
Oat	34.20	43.30	45.72	47.14
Grazing vetch	41.30	46.19	52.75	51.23
P value	*	*	**	n.s
Cv%	10.5	9.6	12.9	6.3

*,** = significant at $p<0.05$ and 0.001 respectively; n.s = not significant ($p>0.05$)

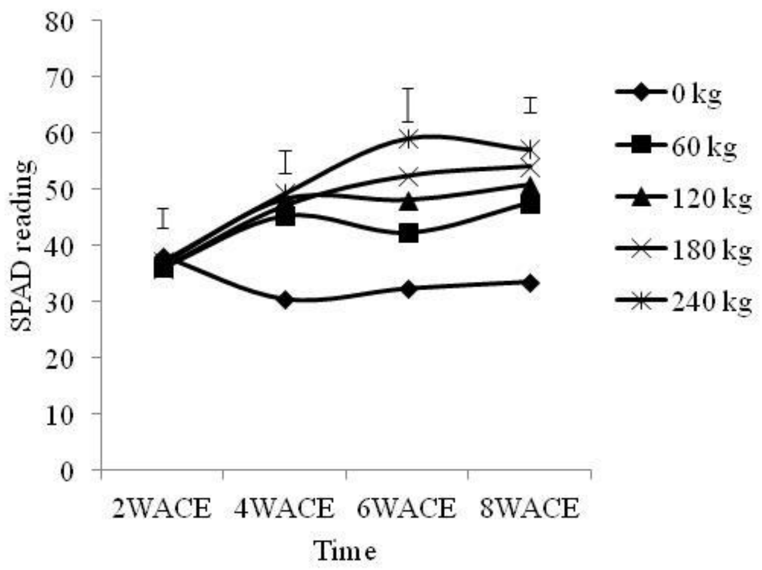


Figure 6.1 Effects of nitrogen fertilizer rate (kg ha^{-1}) on relative leaf chlorophyll content as measured using the SPAD meter

4.4.1.2 Maximum plant height

The cover crop type × fertilizer rate interaction effect on maximum plant height was significant ($p<0.05$). Grazing vetch gave the tallest plants when no fertilizer was applied. However, plant height increased with increase in fertilizer rate in oat and weedy fallow treatments but grazing vetch did not respond (Fig. 6.2). However, beyond an N fertilizer rate of 60 kg ha^{-1}, there were no differences in plant height between the cover crops.

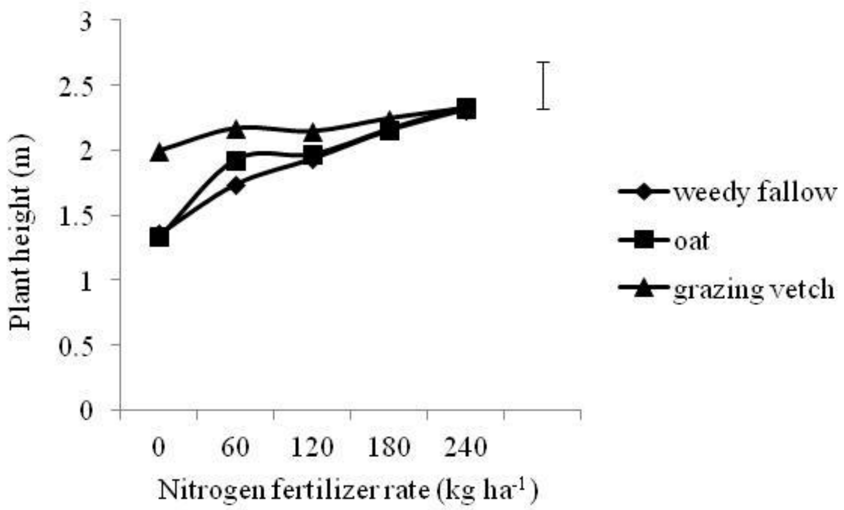


Figure 6.2 Effect of winter cover crop type and fertilizer rate interaction on plant height

4.4.1.3 Maize grain and stover yield, harvest index (HI) and grain N concentration

The cover crop type × fertilizer rate interactions effects on the above parameters were not significant ($p>0.05$). Cover crop type and fertilizer effects were however significant ($p<0.05$) on maize grain yield (Fig 6.3). Grazing vetch gave highest mean grain yield (7.33 ± 0.36 Mg ha^{-1}) than oat (5.19 Mg ha^{-1}), and weedy fallow (4.70 Mg ha^{-1}). The trend was also similar for stover yields i.e. grazing vetch (7.87 Mg ha^{-1}), oat (5.64 Mg ha^{-1}) and weedy fallow (5.73 Mg ha^{-1}). Maize grain yield increased with fertilizer rate up to 180 kg N ha^{-1} (Fig. 6.3). Grazing vetch gave higher grain yields at all N fertilizer rates than either oat or weedy fallow while grain yield for oat and weedy fallow treatments were similar at all fertilizer rates (Fig. 6.3).

The graph (Fig 6.3) also shows that grazing vetch without fertilizer gave maize yield equivalent to at least 120 kg ha^{-1} N applied to the weedy fallow. The fertilizer equivalent for oat was 0, as its yield levels were similar to those of weedy fallow.

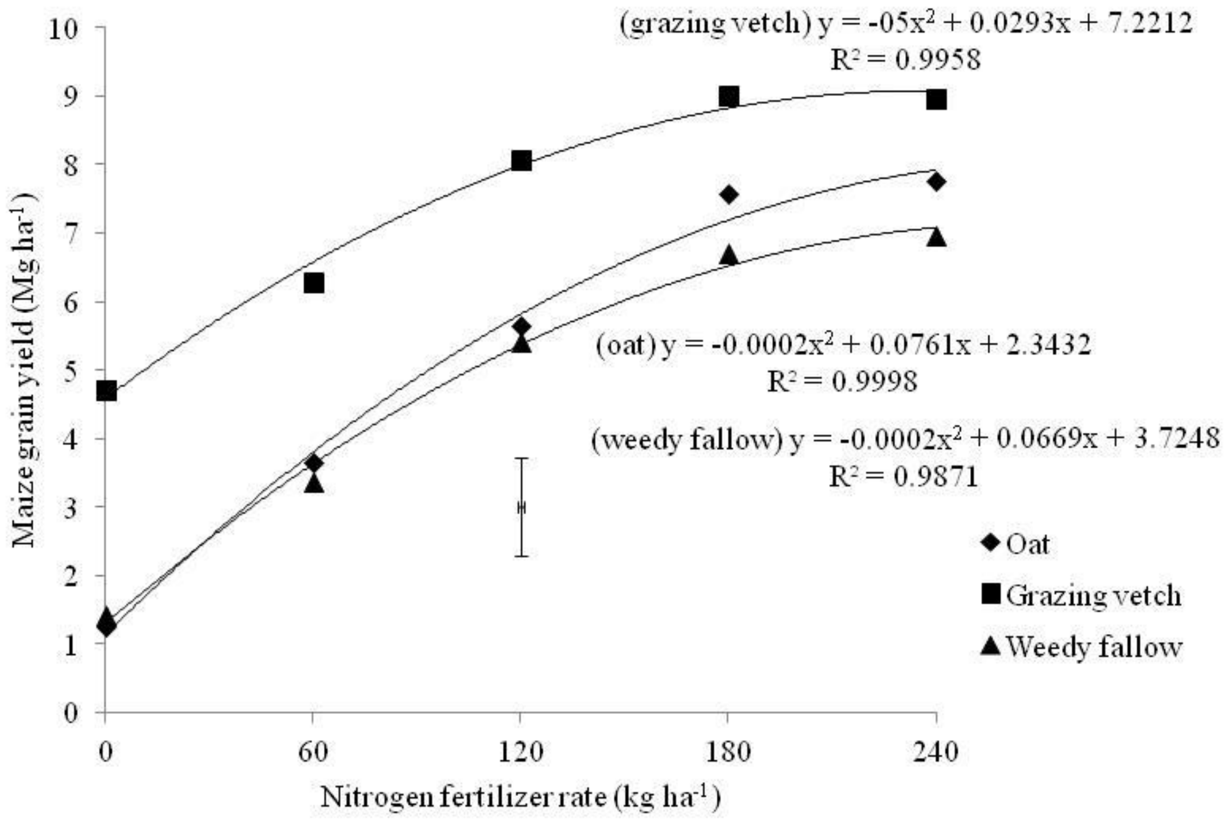


Figure 6.3 Effect of winter cover crop type and fertilizer rate on grain yield in the 1st season (2009/10)

The HI also significantly increased with increasing fertilizer rate between 60 and 120 kg ha^{-1}, but the effect of cover crop type was not significant (Fig. 6.4). Grain N content increased significantly between 0 and 240 kg ha^{-1} N (Fig. 6.5). Winter cover crop type effects on grain N were however not significant (Fig. 6.5).

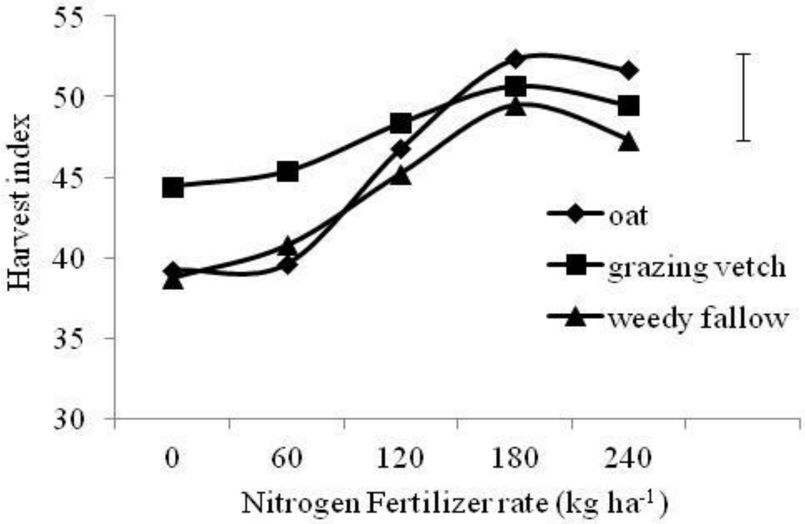


Figure 6.4 Effect of cover crop type and fertilizer rate on harvest index in 1st season (2009/10)

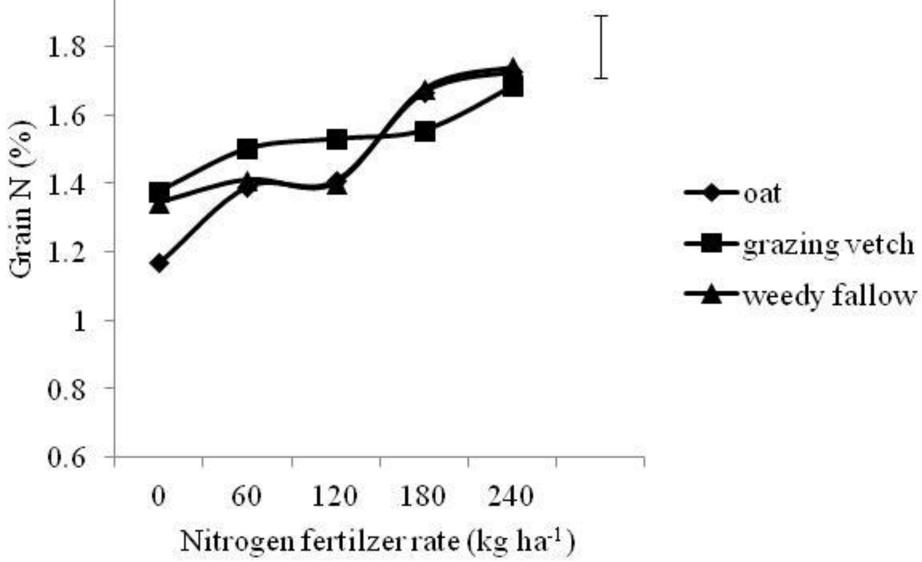


Figure 6.5 Effect of winter cover crop type and nitrogen fertilizer rate on grain nitrogen concentration in 1st season (2009/10)

4.4.1.4 Nitrogen use efficiency indices

Cover crop type effects were significant ($p<0.05$) and grazing vetch gave a mean P*f*P of 64.4 ± 5.9 kg grain kg^{-1} N applied, which was higher than oat and weedy fallow which had P*f*P's 44.1 and 34.7 kg grain kg^{-1} N, respectively. Fertilizer effects were also significant, and the P*f*P decreased significantly between 60 – 240 kg N ha^{-1} (Fig. 6.6). All effects on AE were not significant ($p>0.05$) (see Appendix 6).

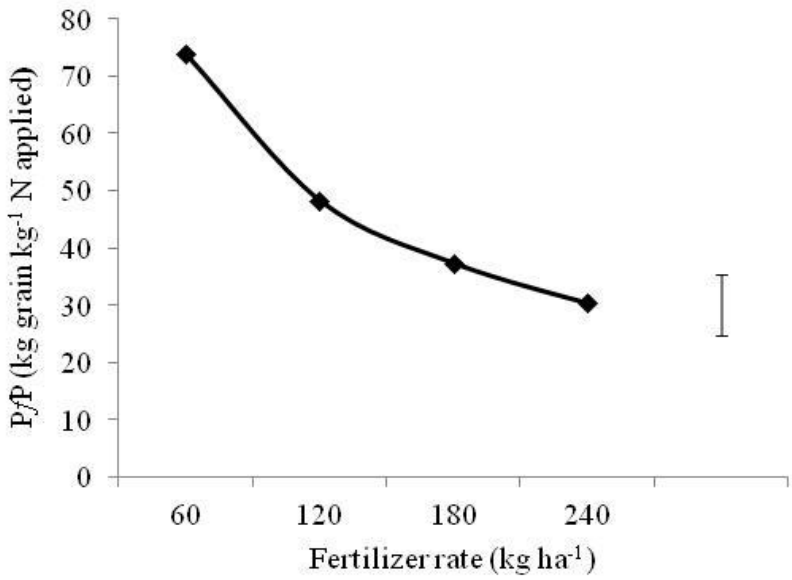


Figure 6.6 Effects of nitrogen (N) fertilizer rate on the partial factor productivity (P*f*P)

6.3.3 Effects of cover crop type and fertilizer rate on grain yield in 2nd season (2010)

The cover crop type × fertilizer rate interaction was significant ($p<0.05$). As illustrated in Figure 6.7, grazing vetch gave the highest maize yield even when no fertilizer was applied. However, at 60 kg N ha^{-1}, the maize grain yields for both vetch and oat were almost similar. This was also the case for oat and weedy fallow at 120 kg N ha^{-1}, where maize grain yield were nearly the same, i.e 8.5 and 8.3 Mg ha^{-1} (Fig. 6.7).

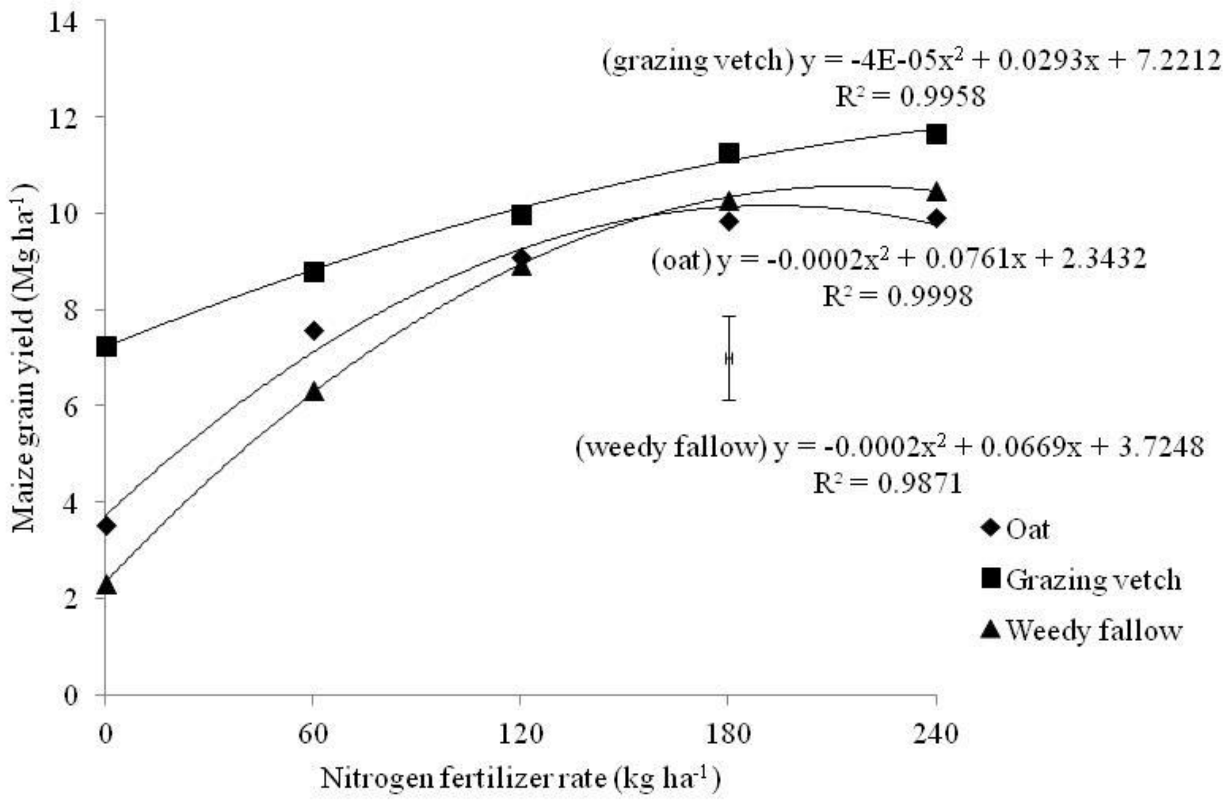


Figure 6.7 Effect of winter cover crop type × fertilizer rate interaction on maize grain yield in the 2nd season (2010/11)

The graph (Fig 6.7) also shows that grazing vetch without fertilizer gave maize yield higher than 60 kg ha^{-1} N applied to the weedy fallow. The fertilizer equivalent for oat was 0, as its yield level was similar to weedy fallow at all fertilizer rates (based on the error margin).

6.3.4 Effects of cover crop type and fertilizer rate on profitability based on dominance and marginal analysis

In the two maize seasons, the highest net benefits were obtained at 180 kg ha^{-1} for both oat and grazing vetch (Table 6.3). The TVC were highest on the grazing vetch due to the cost of grazing vetch seed (Table 6.3). Dominated treatments were eliminated from further analysis and are shown in (Table 6.4). The dominated treatments are those which would make farmers incur additional costs in inputs and yet realize a loss in net benefits.

Table 6.3 Marginal analysis for winter cover crop (cc) type and fertilizer rate effects on maize grain yield

	Oat					Grazing vetch					Weedy fallow				
N fertilizer rate (kg ha^{-1})	[4]**0**	**60**	**120**	**180**	**240**	**0**	**60**	**120**	**180**	**240**	**0**	**60**	**120**	**180**	**240**
Grain yield (2010) (kg ha^{-1})	1246	3643	5643	7571	7857	4714	6286	8071	9000	8571	1424	3357	5424	6714	6571
Grain yield (2011) (kg ha^{-1})	3519	7573	8871	9863	9919	7255	8794	9892	11571	11674	2311	6341	8832	10274	10489
[1]GB (2010)	2181	6375	9875	13249	13750	8250	11001	14124	15750	14999	2492	5875	9492	11750	11499
GB (2011)	6158	13253	15524	17260	17358	12696	15389	17311	20249	20429	4044	11097	15456	17980	18356
Variable costs															
Cover crop seed	110	110	110	110	110	575	575	575	575	575	0	0	0	0	0
Planting cc	500	500	500	500	500	500	500	500	500	500	0	0	0	0	0
N fertilizer	0	745.7	1491	2237	2983	0	745.7	1491.4	2237	2983	0	745.7	1491	2237	2983
Fertilizer application	0	400	400	400	400	0	400	400	400	400	0	400	400	400	400
TVC	610	1756	2501	3247	3993	1075	2221	2966	3712	4458	0	1146	1891	2637	3383
[2]NB (2010)	1571	4619	7374	10002	9757	7175	8780	11158	12038	10541	2492	4729	7601	9113	8116
[2]NB (2011)	5548	11497	13023	14013	13365	11621	13168	14345	16537	15971	4044	9951	13564	15343	14973

[1]GB = Gross benefit, monetary values are in SA rand; [2]NB = Net benefits

Table 6.4 Dominance analysis of the effects of winter cover crops and fertilizer on profitability

Treatment	TVC	Net benefits	
		2010	2011
weedy fallow with no N fertilizer	0	2492	4044
†Oat with no N fertilizer	610	1571D	5548
grazing vetch with no N fertilizer	1075	7125	11621
Weedy fallow with 60 kg N ha^{-1}	1146	4729D	9951D
Oat with 60 Kg N ha^{-1}	1756	4619D	11497D
Weedy fallow with 120 kg N ha^{-1}	1891	7601	13564
Grazing vetch with 60 kg N ha^{-1}	2221	8780	13168D
Oat with 120 kg N ha^{-1}	2501	7374D	13023D
Weedy fallow with 180 kg N ha^{-1}	2637	9113	15343
Grazing vetch with 120 kg N ha^{-1}	2966	11158	14345D
Oat with 180 kg N ha^{-1}	3247	10002D	14013D
Weedy fallow with 240 kg N ha^{-1}	3383	8116D	14973D
Grazing vetch with 180 kg N ha^{-1}	3712	12038	16537
Oat with 240 kg N ha^{-1}	3993	9757D	13365D
Grazing vetch with 240 kg N ha^{-1}	4458	10541D	15971D

† All treatments whose net benefits are marked with a 'D' are dominated and were therefore left out of further analysis

All oat treatments were dominated in the 1st season (Table 6.4) and the highest MRR (622%) was obtained from grazing vetch with a N fertilizer application rate of 120 kg ha^{-1} (Table 6.5). The weedy fallow with a N fertilizer rate of 120 kg ha^{-1} gave a low marginal rate of return of 58%. In the 2nd season, the highest MRR of 1306% was obtained from the grazing vetch with no N fertilizer treatment (Table 6.5).

Table 6.5 Marginal rate of return analysis for non dominated treatments (2010-2011)

Treatment	TVC	Net benefits	MRR **(%)**
2010			
weedy fallow with no N fertilizer	0	2492	
grazing vetch with no N fertilizer	1075	7125	431
Weedy fallow with 120 kg N ha^{-1}	1891	7601	58
Grazing vetch with 60 kg N ha^{-1}	2221	8780	357
Weedy fallow with 180 kg N ha^{-1}	2637	9113	80
Grazing vetch with 120 kg N ha^{-1}	2966	11158	622
Grazing vetch with 180 kg N ha^{-1}	3712	12038	118
2011			
weedy fallow no N fertilizer	0	4044	
oat no fertilizer	610	5548	247
grazing vetch no N fertilizer	1075	11621	1306
Weedy fallow with 120 kg N ha^{-1}	1891	13564	238
Weedy fallow with 180 kg N ha^{-1}	2637	15343	238
Grazing vetch with 180 kg N ha^{-1}	3712	16537	111

6.4 DISCUSSION

Nitrogen fertilization is important for increasing maize yield as evidenced by significant ($p<0.05$) differences between the fertilized and the 0 N treatments in this study. Under well watered conditions, N application accounts for most of the variations in maize yield (Muchow, 1998). Grazing vetch not only gave the highest winter cover crop biomass yield, but also the highest residue N content. Therefore grazing vetch effects on improving grain yield, leaf chlorophyll and plant height can be credited to its ability to improve N supply. Yield improvements from high biomass yielding vetch winter cover crops with N fertilizer replacement values of up to 200 kg ha^{-1} have been reported by numerous other researchers (e.g. Ebelhar *et al.*, 1984, Frye *et al.*, 1988 and Blevins, 1990).

With increasing N supply, N uptake may increase beyond minimum requirement for a given yield potential, hence lower NUE. This N uptake is in excess of what is required for grain and may be referred to as luxury uptake. A diminishing-return relationship between maize grain yield and increasing fertilizer N was evident in all treatments for fertilizer rate above 180 kg ha^{-1} and the result suggest that the maximum yield potential of maize in this system lies below the blanket recommendation of 220 kg ha^{-1} (FSSA, 2007) for irrigated maize. Luxury N uptake at higher N fertilizer application rates can result in higher grain N concentrations, but reduced N fertilizer productivity (P*f*P). The N concentration of the grain reflects the grain protein content and thus the grain nutritional quality (Sinclair, 1998). According to Mason & D'croz-Mason (2002), increasing N rate can result in a higher crude protein concentration in maize, which would imply better human nutrition.

Increasing indigenous soil N supply and the efficiency of applied N utilization are equally important for improving P*f*P of N fertilizer. P*f*P values are generally >70 kg grain kg^{-1} N at low rates of N or in very efficiently managed systems (Doberman, 2007; Roberts, 2008). In this study, the highest P*f*P's for grazing vetch and oat (64.4 and 44.1 respectively) were obtained at the low fertilizer rate of 60 kg N ha^{-1} (Fig. 6.6), which suggests that there is room to improve N use efficiency in the systems. Appropriate selection of winter cover crop termination date is one strategy for improving the synchrony between residue N and maize uptake for improving NUE. Therefore a research study is required for oat and grazing vetch winter cover crops with regard to this matter in the maize based systems.

This study also showed that N fertilizer rates can be reduced after a grazing vetch winter cover crop by up to 120 kg N ha^{-1} (Fig. 6.3). The high MRR for grazing vetch achieved with no fertilizer (Table 6.5) suggests that where water is available, grazing vetch should be considered as a potential N source for profitable maize production as available N in soil is efficiently used. A low MRR may discourage farmers from adopting winter cover crops in maize based systems. Doane *et al.* (2009) also emphasized the benefit of legume winter cover crops in reducing the amount of N fertilizer required to maintain productivity in irrigated no till maize production. Growing maize without using inorganic fertilizers and relying on organic residues as a source of nutrition could be an important step towards profitable organic farming for the smallholder farmers of the EC. Profits can even be further increased if farmers retained and used their own seeds, rather than purchase as the current price of vetch seed is high.

The effects of N fertilization on the yield of maize following residues of wide C:N ratio under no till have been investigated extensively and there is evidence suggesting that N demand can be increased by as much as 25% to counter short term N immobilization by the crop residues (Randall & Bandel, 1991, Archer *et al.*, 2008). A C:N ratio of approximately 20-30 is used as a threshold delineating mineralization and immobilization (Clark, 2007). Nitrogen immobilization is normally expected from small grain residues of wide C:N ratio, which would result in an increased N demand. In this study it was observed that oat effects on grain yield were similar to weedy fallow, thus oat did not result in increased N demand as reported elsewhere (Clark, 2007). The C:N ratio of oat residues in this study (28) was within the critical range and would not limit mineralization and that probably explains the lack of immobilization in this study.

Soils with high sand contents as found in smallholder farmlands of the EC generally do not hold nutrients well, especially mineral N, and leaching losses of mineral N may be suffered from irrigation. Low temperatures at the beginning of the summer season may also slow down decomposition and mineralization of N from organic sources. These facts may partially explain why there were no significant differences in nitrate-N, ammonium-N or total mineral N in the soil at planting maize between grazing vetch, oat and the weedy fallow.

6.5 CONCLUSIONS

Grazing vetch can increase maize growth, grain yield response to N fertilizer, NUE and profitability for fertilizer rates below 180 kg N ha^{-1}. Oat effects however on maize yield and NUE are generally similar to weedy fallow. Grazing vetch without N fertilizer gave maize yield equivalent to up to 120 kg ha^{-1} N applied to the weedy fallow, suggesting that N fertilizer rates can be reduced following grazing vetch. Based on the P*f*P, the highest efficiencies in utilization of fertilizer N for maize yield improvement under grazing vetch and oat were obtained at 60 kg N ha^{-1} and declined thereafter with any further increases in fertilizer application rate. No N fertilizer benefit was however, obtained with oat. Although grazing vetch seed is relatively more expensive, it can produce enough maize yield response to pay its way in an irrigated maize-based CA system, based on its high MRR to increasing N fertilizer rate. No additional fertilizer may be required following oat winter cover crops to counter possible immobilization of N when compared with weedy fallows.

5 WINTER COVER CROPS AND FERTILIZER EFFECTS ON THE SEEDBANK OF PROBLEMATIC WEEDS IN A MAIZE-BASED CONSERVATION AGRICULTURE SYSTEM

Abstract

Apart from soil fertility problems, weeds are another major problem causing low maize yields in maize based smallholder systems of the Eastern Cape (EC). The practice of conservation agriculture (CA) for soil fertility improvement demands the use of herbicides for effective weed control. Proponents of CA argue that herbicide requirement would decline over time as soil cover practices and organic matter buildup causes a decline of weed seedbanks. A field experiment was established during the 2007 winter season at the University of Forth Hare Farm (South Africa) to investigate the impacts of winter cover crops (grazing vetch {*Vicia darsycapa*}, oat {*Avena sativa*}) and fertilizer on the seedbank of problematic weeds in a maize-based CA system. Seedbank sampling (0 – 5 and 5 – 20 cm depths) took place at maize planting in the fourth year of continuous practice (2010) and the weed seedbank density was analyzed using a seedling emergence method. Oat and grazing vetch were more effective than the weedy fallow in reducing seedbank density of *Digitaria sanguinalis*, *Eleusine indica*, *Amaranthus retroflexus* and *Datura stramonium* at 0 – 5 cm soil depth, causing weed seed reductions of 30 - 70%. Fertilizer application resulted in a 41.6% *A. retroflexus* seed reduction on the weedy fallow rotation, but was not important on oat and grazing vetch rotations. Grazing vetch effects on depleting weed seed density of *D. sanguinalis*, *A. retroflexus* and *E. indica* were not affected by depth, whilst those of oat were more effective at 0 – 5 cm than 5 – 20 cm depth. Weed species diversity at the seedbank level was not affected by the treatments. Seedbank density was negatively correlated with biomass input from maize and cover crops. It was concluded that in low input maize-based CA systems as found in the EC, high biomass yielding oat or grazing vetch winter cover crops can hasten depletion of problematic weeds from seedbanks, leading to reduced weed pressure during maize growth.

Key words: Biomass; grazing vetch; oat; weed management

6.6 INTRODUCTION

Conservation agriculture (CA), a practice where soil disturbance is minimal and permanent soil cover is maintained through cover crops and crop residues, is becoming increasingly acceptable to farmers across the world. When done correctly, it has great potential to decrease farmers' input costs and increase yields in a sustainable manner (FAO, 2008). Although CA holds potential for sustainable crop production coupled with solving land degradation problems resulting from conventional agricultural practices in smallholder farming communities of the Eastern Cape (EC) Province of South Africa, its adoption is in early stages and at best modest due to several factors, including problems of weed management.

Maize (*Zea mays L.*) is the most important crop grown by resource-poor farmers under smallholder irrigation in the EC province and there are serious economic and political forces that collectively encourage increased annual maize production. Therefore farmers grow maize continuously resulting in proliferation of problematic grass weeds and sedges (Blackshaw, 1994), due to a consistently hospitable environment for weeds that have phenological and physiological similarities to the maize crop. These include *Digitaria sanguinalis*, *Cyperus esculentus* and *Cynodon dactylon* which are some of the problematic weeds that emerged in significant numbers during growth of summer maize in the ongoing CA field trial (Chapters 3, 4 and 5). Soils in smallholder farming systems contain a large reservoir of seeds of these problematic weeds and in severe cases; they cause an abandonment of fields (Fanadzo *et al.,* 2010).

Tillage is important for weed control in smallholder maize production in the EC (Jourbet, 2000; Fanadzo, 2007). Reduced tillage causes a buildup of weed seeds on the soil surface (Swanton *et al.,* 2000), where seed fate could be strongly influenced by crop residues. Abandonment of tillage towards CA may pose a challenge for the farmers, who can neither afford herbicides nor possess the equipment and technical expertise required for effective chemical weed control. Whist the practice of CA demands the use of herbicides for effective weed control, proponents of CA argue that herbicide requirement would decline over time as the increase in soil cover prevents weed emergence and cause a decline of weed seedbanks. Abundance of residues from a previous crop conserves moisture and increases the organic matter content in the upper soil layer (Chapter 3), encouraging biotic activity (Power *et al.,* 1986). According to Adedeji (1984) and Baldoni *et al.* (1999), seedbank depletion by surface mulches may be ascribed to conditions that increase loss of weed seed viability, predation and non-recruitment of new seeds.

Winter cover crops can be used to increase biomass input and crop residue cover in the irrigated maize-based cropping systems of the EC. Oat (*Avena sativa*) and grazing vetch (*Vicia darycapa*) are examples of winter cover crops that have been found to provide high amounts of biomass (> 6 Mg ha^{-1}), and resulted in improved maize yields (Chapter 5). Oat biomass yields have been found to be increased by fertilizer whilst those of grazing vetch were not (Chapter 3). Winter cover crop mulch effects on weed growth on conversion to CA have been reported in irrigated maize-based cropping systems of the

EC (Murungu *et al.,* 2010b). There is however no literature that clearly points out the effect of mulch on seed bank dynamics in low input maize-based CA systems.

Several soil-biological, physical and chemical processes, including fertilizer effects are associated with seedbank dynamics and weed emergence (Gallagher & Cardina, 1998 and other authours therein). The species composition and physiological states of the weed seeds present in a soil seed bank are integrated over a range of environmental and management conditions confronting a particular agriculture system (Davis *et al.,* 2005). The primary objective of this study was therefore to investigate the effects of oat, grazing vetch winter crops and fertilizer application on the seedbank size of problematic weeds following four years of continuous CA practice. A secondary objective was to relate the seedbank density to cover crop biomass yields and weed emergence in the maize crop.

6.7 MATERIALS AND METHODS

6.7.1 Experimental site, design and layout

The study was conducted at the University of Fort Hare Farm in an ongoing CA field trial established in 2007. The climate and soil type of this site has been described previously (Section 3.2). The pre-trial elemental content of the soil was presented in Table 3.1. The experimental design and the field trial management have been described in section 3.2.1. Two factors were studied, namely; winter cover crop type and fertilizer application to maize. The winter cover crops types were oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) plus a weedy winter fallow, all grown with no fertilizer. This gave a 3 × 2 factorial plus control plots laid out as a randomized complete block design with three replications.

6.7.2 Soil sampling for weed seedbank study

Twelve random soil samples were collected from the 0 – 5 and 5 – 20 cm depths of each plot at the beginning of the 4th year, after cover crop termination and before maize planting. Soil sampling was done from the inner two-thirds of each plot. A small trowel was used for soil sampling at 0 – 5 cm, after clearing the litter layer, and a 7.0 cm diameter precision auger was used for the 5-20 cm depth. Soil from each plot was bulked to form one sample and the samples were air dried and sieved (< 2 mm) to remove coarse fragments and roots. Large weed seeds or propagules that could not pass through the sieve were sorted out and returned to the sieved soil sample.

6.7.3 Weed seed-bank evaluation

A glasshouse germination test was used to determine the weed composition of the seed banks (Gross, 1990). The sieved soil samples were placed in trays of 30 cm diameter × 2 cm depth (1400 cm^3) in a glasshouse set at temperature range of 25- 30°C and the soils were maintained close to field capacity (17% w/w) by regular watering (Plate 6.1). After two weeks, weed seedlings were identified using the weed identification handbook for problematic weeds of South Africa (Bromilow, 1995). They were subsequently counted and then removed. Seedlings that could not be identified were transplanted onto an artificial medium and allowed to grow to maturity before identification. Soil samples were dried for two weeks and then stirred to stimulate germination of weed seeds below the 2 cm soil layer. The experiment was terminated at the end of 3 months when seedling germination ceased. The raw density data for each species was used to calculate Shannon's diversity index (*H′*) (Shannon, 1948), which provides an overall assessment of weed species diversity (Derkensen *et al.,* 1995) as follows:

$$H' = \left(N \log N - \sum n \log n\right) N^{-1};$$

where N is the total weed density (weeds/ m^{-3}) in a plot and *n* is the weed density of each species present in a plot. High values of *H′* would be representative of more diverse communities (Derksen *et al.,* 1995).

Plate 5.1 Weed seed bank evaluation using the glasshouse germination method

6.7.4 Weed biomass yield and species composition under field conditions

Sampling for weed biomass yield and species identification was done at 6 weeks after emergence (WAE) of the maize crop during the 4^{th} year. The weeds species were separated, oven dried to a constant weight at 65°C and weighed.

6.7.5 Data Analysis

Weed seed bank data were subjected to an analysis of variance (ANOVA) to test winter cover crop type × fertilizer × soil depth effects using GenStat Release 12.1. Weed biomass data obtained at 6 WAE was also subjected to ANOVA to test for cover crop type × fertilizer effects. Means were separated using least significant differences (LSD) at $p<0.05$. Winter cover crop type and fertilizer effects on cover crop biomass and maize stover inputs from the field trial have been reported in Chapter 3, and the data is used for correlations to establish relationships between variables and weed seed bank parameters in the current study. Spearman correlation coefficients were derived using GenStat Release 12.1.

6.8 RESULTS

6.8.1 Seed bank composition

The traditionally problematic weeds obtained from the seed bank evaluation across all treatments included *Digitaria sanguinalis, Eleusine indica, Amaranthus retroflexus and* Datura *stramonium.* Other species in the seed banks included *Galinsoga parviflora, Oxalis latifolia, Capsella bursa pastoris, Setaria verticillata, Nicandra physaloides* and *Portulaca oleracea*.

Interaction effects of cover crop type × fertilizer × soil depth on seed bank density for all weeds were not significant (P>0.05). Cover crop type × fertilizer interaction had a significant (P<0.05) effect on the density of *A. retroflexus* but not on *D. sanguinalis, E. indica and D. stramonium* (Table 7.1). The fertilizer application was important for depleting *A. retroflexus* on the weedy fallow rotation, resulting in 41.6% weed seed reduction, but was not important for oat and grazing vetch rotations.

Winter cover crop type × depth interaction effects on *D. sanguinalis*, *A. retroflexus* and *E. indica* were significant except on *D. stramonium* (Table 7.2). Grazing vetch had a greater seed bank reducing effect at both surface (0 – 5 cm) and deeper buried (5 – 20 cm) seeds of *D. sanguinalis* than oat. Effects of grazing vetch on depleting the seed density of *D. sanguinalis, A. retroflexus* and *E. indica* weresimilar at 0 - 5 and 5 - 20cm while those of oat and weedy fallow were more effective at 0 – 5 cm than 5 – 20 cm.

Table 5.1 Interaction effects of winter cover crop type and fertilizer application on the seedbank density (weeds m^{-3} soil) of problematic weeds

	Grazing vetch		**Oat**		**Weedy fallow**		Interaction
	Fertilized	No fertilizer	Fertilized	No fertilizer	Fertilized	No fertilizer	*P* value
Digitaria sanguinalis	6211.8 a	8710.8 ab	11638.2 ab	14637 bc	17350.2 cd	17493 cd	n.s
cv (%)	-------------------- 33.2 --------------------						
Amaranthus retroflexus	4162.6 a	6304.6 ab	7261.4 b	5833.4 ab	8568 b	14622.7 c	0.021
cv (%)	-------------------- 38.6 --------------------						
Eleusine indica	3334.4 a	4998 a	4519.6 a	7618.4 ab	11067 b	11352.6 b	n.s
cv (%)	-------------------- 36.7 --------------------						
Datura stramonium	4405.38 a	3927 a	4048.4 a	3334.4 a	6426 b	6640.2 b	n.s
cv (%)	-------------------- 41.0 --------------------						

Means followed by the same letter within a row are not significantly different at $p<0.05$; n.s = not significant ($p>0.05$). The cv% is for every row.

Table 5.2 Interaction effects of winter cover crop type and soil depth on the seedbank density (weeds m^{-3} soil) of problematic weeds

	Grazing vetch		**Oat**		**Weedy fallow**		Interaction
	0 – 5 cm	5 – 20 cm	0 – 5 cm	5 – 20 cm	0 – 5 cm	5 – 20 cm	*P* value
Digitaria sanguinalis	7140 a	6283.2 a	15708 c	10567.2 b	24276 d	10567.2 b	0.021
cv (%)			-------------------- 33.2 --------------------				
Amaranthus retroflexus	6190.3 ab	4284 a	9874.6 b	3213 a	16422 c	6768.7 ab	0.016
cv (%)			-------------------- 38.6 --------------------				
Eleusine indica	5355 ab	2977.4 a	8089.6 b	4048.4 a	15829.4 c	6590.2 ab	0.042
cv (%)			-------------------- 36.7 --------------------				
Datura stramonium	6190.4 c	2142 a	5590.6 c	1785 a	9403.3 d	3662.8 b	n.s
cv (%)			-------------------- 41.0 --------------------				

Means followed by the same letter within a row are not significantly different at p<0.05; n.s = not significant (p>0.05)

Table 5.3 Correlation matrix for biomass input, weed species biomass in maize crop and seedbank weed density

	Seed bank (0 – 5 cm)			**Seed bank (5 – 20 cm)**		
	E. indica	*A. retroflexus*	*D. sanguinalis*	*E. indica*	*A. retroflexus*	*D. sanguinalis*
[1]Winter cover crop biomass	-0.387*	-0.272 n.s	-0.41*	-0.428*	-0.514*	-0.179 n.s
[2]Total biomass input	-0.621**	-0.491*	-0.703**	-0.621**	-0.425*	-485*
Weed specie biomass	-	0.677**	0.705**	-	0.415*	0.529*

n.s, not significant; *, **, significant at 0.05 and 0.01 probability level, respectively

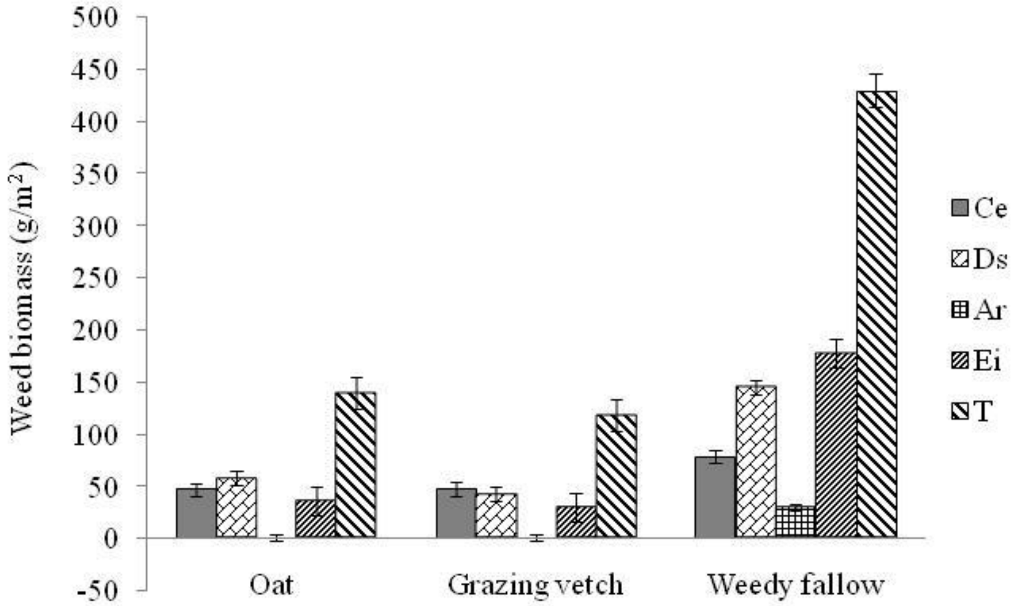
[1] Winter cover crop biomass input summed over 4 years

[2]Maize stover biomass + winter cover crop biomass summed over 4 years

Oat and grazing vetch were more effective than the weedy fallow in reducing *D. sanguinalis, A. retroflexus, E. indica* and *D. stramonium* seedbank density at 0 – 5 cm (Table 7.2). When compared to the weedy fallow, grazing vetch reduced the density of these species by 70.5%, 62%, 66.2% and 34.2%, respectively. Oat on the other hand reduced them by 35.3%, 39.9%, 48.9% and 40.5%, respectively. Effects were the same across all winter cover crop types for seed banks of *A. retroflexus* and *E. indica* at 5 – 20 cm (Table 7.2). All factors and interactions had no significant ($p>0.05$) effect on weed diversity at the seedbank level as measured using Shannons *H′*. The overall mean for *H′* across treatments was 0.86 ± 0.054 SED.

6.8.2 Weed biomass at 6 WAE of maize

The major problematic weeds that emerged during early maize growth and development across the treatments were *D. sanguinalis, C. esculentus, E. indica* and *A. retroflexus*. Winter cover crop type × fertilizer interaction had no significant ($p>0.05$) effect on biomass of the different species. However, winter cover crop type had a significant effect on weed biomass (Fig. 7.1). The weedy fallow gave higher biomass of *D. sanguinalis, C. esculentus, E. indica* and *A. retroflexus* than oat and grazing vetch. Fertilizer had no significant ($p>0.05$) effects on biomass yield of individual species, but significantly reduced total biomass of problematic weeds by 12.9%.



(Ce = *C. esculentus*, Ds = *D. sanguinalis*, Ar = A. *retroflexus*, Ei = *E. indica*, T = total weed biomass).

Figure 5.1 Effects of winter cover crop type on biomass of problematic weeds at 6 WAE in the 4th year of continuous maize-winter cover crop rotation

6.8.3 Spearman's correlations between cover crop biomass yields, weed biomass in maize crop and seed bank parameters

There were significant ($p<0.05$) negative correlations between biomass input and weed seed density for the various species at both 0 – 5 cm and 5 – 20 cm, except for *A. retroflexus* and *D. sanguinalis* which were not significant at 0-5 cm and at 5 – 20 cm respectively (Tables 7.3). There were significant positive correlations between *A. retroflexus* and *D. sanguinalis* weed biomass in the maize crop at 6 WAE and their seedbank density (Table 7.3). The correlations were stronger for weed seed density at 0 – 5 cm than at 5 – 20 cm (Table 7.3).

6.9 DISCUSSION

Results from the current study have demonstrated that weed seed bank density of both surface and buried problematic weeds is decreased by including oat and grazing vetch winter cover crops to these systems, as opposed to leaving the land fallow in winter (Table 7.1, 7.2). Most research carried out elsewhere on cover crops effects on weed seed banks is from conventional systems, and compares ploughed-in winter cover crops with those not using cover crops (Derkensen *et al.*, 1995; Baldoni *et al.*, 1999; Gallager *et al.*, 1999). Weed seedbank depletion by surface mulches as provided by winter cover crops can be credited to mulch effects on weed seed production and seed loss through predation and pathogenesis (Gallager *et al.*, 1999). According to Gallager *et al.* (1999), persistence of weed seed buried deep in the soil is a function of weed seed dormancy and resistance of weed seeds to microbial decay. Soil microbial activity is generally associated with SOM content. Consequently, fallow management that results in return of significant organic materials to the soil (such as inclusion of oat and grazing vetch winter cover crops) would be expected to enhance soil microbial activity and potentially increase the level of microbial-induced weed seed decay.

Although *Cyperus esculentus* did not emerge in significant numbers in the glasshouse study (for it to be measurable), it was a major weed that emerged during maize growth in the 4^{th} year in the field. This suggests that either a stimulus was present in the field, allowing its germination or that the glasshouse conditions were not favourable to break dormancy of the seeds. *C. esculentus* dormancy is broken by several months of dry storage at room temperature or moist storage at 10°C (Justice & Whitehead, 1946). *Cyperus esculentus* has a reputation for being difficult to control as the weed survives seasons of harsh weather conditions through prolific seed and tuber production. It is an early summer weed and establishes rapidly with the onset of early rains. No till could promote longevity of *C. esculentus* tubers (Halvorson, 2003).

In the absence of mulch on the weedy fallow, fertilizer application was important for depleting *A. retroflexus* (Table 7.1). Fertilizer application is important for good early growth and establishment of maize for fair competitiveness against weeds. The fertilizer rate tested in this study was low (i.e. 60 kg N ha^{-1}), in line with the practice of resource poor smallholder farmers of the EC. This finding emphasizes the importance of soil fertility improvement in weed management, because, even at low rates, fertilizer can have significant effects on seedbank density of some problematic weed species.

Grazing vetch is preferable with regard to *D. sanguinalis* control as it had a greater seed bank reducing effect of both surface (0 – 5 cm) and buried (5 – 20 cm) seeds of *D. sanguinalis* than those of oat and weedy fallow. Within the scope of this study, we cannot fully explain the mechanisms behind this observation. Murungu *et al.* (2010) found grazing vetch more preferable as a cover crop in low fertilizer input systems than oat due to its ability to fix N_2, its fast decomposition and rapid release of nutrients. As a result of their fast decomposition, grazing vetch residues may be generally more effective than oat in supporting biological seed loss mechanisms such as microbial decay and predation. *Digitaria sanguinalis* is an aggressive colonizer which has the ability to form runners and tillers for effectively colonizing mulched surfaces. It can generate roots along its prostate stems, and stems torn out and left on the ground can begin a new life. It also thrives well under no till. Mohler & Callaway (1995) reported that no till increased the seedbanks of *Digitaria* when compared to tillage under sweet corn.

Lowering agro-ecosystem biodiversity is undesirable as it may create new niches for some once unimportant weeds to become problematic. Mainly narrow-leaf weeds (C.

esculentus, *D. sanguinalis* and *E. indica*) emerged in significant numbers under winter cover crop residues during early maize growth whilst *A. retroflexus* (a broadleaf) was present on the weedy winter fallow. This observation suggests that oat and grazing vetch winter cover crop residue mulches are likely to cause a shift to more grass weeds than broad leaves as it was in the conventional systems. This was in agreement with Delate & McKern (2004), who found that a rye cover crop mulch had no significant effect on grass weeds, although it had a significant effect on broadleaf weeds. Because of the nature of their leaf arrangement, grass weeds and sedges have a great capacity of emerging through the residue and becoming established. Plate 6.2 shows the ability of *C. esculentus* to emerge from under a thick layer of oat mulch.

Plate 5.2 Narrow leafed weeds like *Cyperus esculentus* have an ability to emerge and thrive in mulched conditions

As demonstrated in this study, winter cover crop biomass is also important in the depletion of both surface and buried weeds. High amounts of oat and grazing vetch residues are also effective as a weed barrier during early maize emergence as shown in Plate 7.3.

Future research should focus on methods for enhancing cover crop biomass yield as a means of further hastening problematic weed seed losses from seed bank.

Plate 5.3 Weed smothering effects of oat mulch against a no winter cover crop mulch surface (right).

6.10 CONCLUSIONS

In low input maize-based CA systems as found in the EC, inclusion of oat or grazing vetch winter cover crops can hasten depletion of problematic weeds from seedbanks, leading to reduced weed pressure during maize growth. Fertilizer application to maize at 60 kg N ha^{-1} might not have significant impacts on seedbank density, or on modifying winter cover crop effects on seedbank density of all major problematic weeds except *A. retroflexus*. Grazing vetch winter cover crops hold better promise than oat in depletion of seedbanks of *D. sanguinalis* and *E. indica.* The winter cover crop mulches may allow proliferation of narrow leafed weeds such as *C. esculentus* in the maize crop.

7 GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 GENERAL DISCUSSION

Inadequate biomass input is suspected to be the major reason why, in low fertilizer input maize-based smallholder systems of the Eastern Cape (EC) province in South Africa (SA), conservation agriculture (CA) has not provided soil fertility benefits. It was hypothesized in this study, that inclusion of high biomass yielding oat (*Avena sativa*) and grazing vetch (*Vicia darsycapa*) winter cover crops in rotations could result in realization of these benefits, in the form of improved soil organic matter (SOM) and availability of essential plant nutrients. This study naturally emerged in continuation of preliminary research on CA in the Eastern Cape (EC) province of SA which screened a number of cover crop species for biomass production in smallholder maize-based systems (Murungu, 2010). The major objective of this study was to quantify the benefits of oat, grazing vetch winter cover crops and fertilizer (applied to winter cover crops and maize) to soil fertility in the maize-based systems in order to provide a scientific basis for making recommendations. This chapter ties up together the different findings from chapters in the thesis and comes up with an overall picture of the study.

Nitrogen (N) and phosphorus (P) are the most important elements applied as fertilizer to maize produced in the EC and world prices of these fertilizers are on the rise because their production currently fails to meet demand (FAO, 2008). There is merit in technologies that allow resource poor smallholder farmers as those found in the EC to apply less of these fertilizers, or at least increase the benefits of using the fertilizers. Soil organic matter, which was increased through oat and grazing vetch winter cover crops in the current study, is a good source of N and P (Brady & Weil, 2008). Particulate organic matter (POM) is regarded as the fertilizer property of SOM (Swift & Woomer, 1993) and the winter cover crops give higher amounts of POM than weedy fallows (Chapter 3), thus reading to greater amounts of plant available nutrients as substantiated in Chapters 4 and 5.

Grazing vetch, which gives a high N fertilizer replacement value and marginal rate of return with no fertilizer applied, appears ideal for resource poor farmers who cannot afford mineral fertilizers. Vetch also provides maize yield improvements beyond those attributable to N. An example is soil improvement through biological activity (Folorunso *et al.,* 1992) on low clay content soils similar to the one used in this study. Over a four year period, grain yield of fertilized maize declined sharply on the weedy fallow rotations but remained almost stable on the oat and grazing vetch rotations, demonstrating that winter cover crops can prevent annual yield reductions that are associated with maize monocropping. Both winter cover crops types made contributions on availability of P and Zn in the soil. Recognizing the importance of the Zn to yield improvement on South African soils, many compound fertilizers sold in SA are fortified with 0.5% Zn. The improvements in availability of essential nutrients under winter cover crops not only has benefits on maize growth and yield, but could also improve winter cover crop growth and biomass yield, and mulch benefits on SOM and weeds.

Soil organic matter improvements not only increase soil fertility, but can reduce soil erodibility through enhancing soil aggregation (Larson & Pierce, 1991). Improvement of SOM, hence aggregation, is one way of reversing degradation on soils of the EC that are highly susceptible to erosion. High biomass yielding oat and grazing vetch winter cover crops are therefore proposed as one way of reducing erodibilty of soils, and in turn reducing loss of nutrients from cultivated lands in the EC. Studies however are required to quantify the effects of the winter cover crops on soil aggregate stability, including other physical properties that render a soil's resistance to erosion.

The importance of fertilizer in CA systems is highlighted in many findings from this thesis. Even at the low doses (60 kg N and 30 kg P ha^{-1}), fertilizer was important for increasing biomass input and SOM (especially for oat) (Chapter 3). Fertilizer, together with the winter cover crops was equally important in increasing availability of some essential plant nutrients (Chapter 5) and for increasing maize yield (Chapter 6) and depleting the seedbank of some problematic weeds (Chapter 7). There is therefore a need to promote winter cover crops with fertilizer inputs inorder to enhance benefits. This finding has implications on policy for promotion of CA in the resource poor smallholder of the EC. It is reported that programs initiated during the 1980's to support resource poor smallholder farmers of the EC with fertilizer inputs failed due to poor recovery of loans from participating farmers (Monde *et al.*, 2005). However, as evident from this study, inclusion of winter cover crops in maize-based CA systems would improve maize yield and the profitability of using fertilizer (Chapters 5 and 6) would thus put the farmers in a better position to repay loans. Where inorganic fertilizers are not available, N fixing legumes such as grazing vetch could be promoted as a means of supplying N, whilst animal manures could be used to supply other nutrients such as P, e.g goat manure (Gichangi, 2008). Research on the effects of animal manures on winter cover crop growth, maize yield response and soil fertility improvement in maize-based CA systems may however, be required.

Soil fertility and weed management are critical agronomic practices for increasing crop yield that complement each other and in the absence of good weed control, the benefits of increased soil fertility may not be realized. It is therefore important to evaluate the crop, the management systems effects on soil fertility and the weed management concurrently. Apart from substantially increasing biomass input, SOM content and availability of some essential nutrients, winter cover crops also caused depletion of seedbanks of both surface and deep buried seed (Chapter 7). Thus it may be concluded that high biomass yielding winter cover crops are a one-stop-shop solution to the soil fertility and weed problems experienced by resource poor farmers.

It is to be recommended from this study that for both benefits (maize grain and SOM); fertilizer is better invested on the winter cover crop than the maize crop (Chapter 4). By investing fertilizer on winter cover crops rather than the maize crop, the smallholder farmers also stand to benefit from improved winter cover crop biomass yields, implying better protection against weeds and soil erosion. The increased winter cover crop biomass yields may also hasten depletion of weed seedbanks. Lowered abundance of weeds means that farmers can spent less labour on weeding. There is drudgery associated with hoe weeding and in most cases, weeding is carried out by women and children (Giller *et al.*, 2009). It has been demonstrated in this study that weed seedbank densities of problematic weeds can be reduced significantly by winter cover cropping, and ideally, this would result in improved quality of life. Increasing soil fertility and maize growth enhances competiveness and tolerance to weed competition (Mohammadi, 2007). Improved maize growth under winter cover crops resulting from enhanced soil fertility therefore means more stover for SOM formation, as well as weed smothering. Grazing vetch, through its effects on soil N, increases grain N content and this, presumably could mean increased grain protein and better nutrition from maize for the smallholder farmers. It is reported that many resource poor families in the EC cannot afford meat as a source of protein.

Weakly weathered soils in low rainfall smallholder farmer areas of the EC do not contain large amounts of kaolinite (1:1) clays, or Fe and Al oxides (Mandiringana *et al.,* 2005), and therefore have low to very low P fixation capacity. There is evidence which suggest that SOM reduces P fixation through its interaction with soil components on P fixation sites (Ohno & Crannell, 1996; Brady & Weil, 2008). Increases in surface (0-5 cm) SOM and P (from winter cover crops, maize stover and P fertilizer application) could saturate the P sorption sites, thus increasing concentrations of soil solution P. If P fertilizer application rates are not adjusted accordingly, the result would be high concentrations of dissolved P in drainage irrigation water. Hence net P losses through deep leaching of P are possible on sandy soils if they receive excess amounts of manure (Sims *et al.,* 1998).

No till results in the formation of continual soil channels and cracks, including earthworm burrows (Sims *et al.,* 1998). Irrigation water carrying dissolved P, including P bound to organic matter particles flows freely through these channels to lower levels of the soil profile, sometimes below the rooting zone. Phosphorus may thus be lost to deep leaching in the CA systems ending up in waterways. Efficient recycling of P is important for sustainability of low fertilizer input systems as well as environmental protection. Further research is therefore required to test the effects the winter cover crops on P recycling in the maize-based CA systems. Large differences in soil C and nutrients (including P) have been found with depth up to 1 m due to management effect in undisturbed systems (e.g. Whitney & Zabowski, 2004). Hence, it may be more comprehensive for future work to determine soil total C and nutrients throughout the rooting depth of maize (1 m) rather than the 0-50 cm depth used for measuring SOM in this thesis.

Whilst the target domain for this study has been smallholder resource poor farmers, it can be stated that the technologies proposed are could also work for commercial farmers who intent to maximize profit, increase maize yields and improve environment sustainability. For commercial farmers, there would be less reliance upon herbicides for weed control in CA systems. When herbicides land on the soil, they usually end up in runoff water and get carried away to nearby streams, lakes and wetlands, where they can contaminate drinking water and other aquatic resources. This can potentially threaten endangered species as well as other non-target organisms for which the effects resulting from exposure are not known. Mulched surfaces are however, unlikely to be effective on weeds that possess phenological characteristics which allow them to colonize mulched surfaces, such as *Cyperus esculentus* and *Digitaria sanguinalis*. Future research studies need to focus on ways to deal with the ‘escapees’, so that they don’t become dominant weeds in maize-winter cover crop rotations.

It should be noted that there are a number of potential disadvantages whenusing winter cover crops in maize-based systems which could decrease their acceptance by smallholder farmers. Foremost among the disadvantages is the fact that it costs money to plant the cover crop and to terminate the cover before planting maize. Using lower limits of recommended seeding rates, at the time of this writing, seed costs for a grazing vetch winter cover crop seeded at 35 kg ha^{-1} would be R600.00 ha^{-1}. The increased cost of the legume seed can however, be offset by the value of the high N fertilizer value in the legume. In other words, grazing vetch can provide enough N to pay its way in the maize based CA systems. Furthermore, money is saved from reduced weed control costs that are possible with high biomass yielding oat and grazing vetch winter cover crops. Economic risks and seeding costs of the legume can be reduced if farmers multiplied and retained their own seed. Oat is palatable to livestock and can re-grow after grazing and thus would fit well into integrated livestock-cropping systems. If left to grow up to maturity, oat can provide an additional benefit of edible grain.

Whilst this study focused on establishing economically optimum nitrogen fertilizer application rates (NAR) for maize yield under winter cover crops, there is also a need to do further research to determine the effects of NAR on environmental sustainability of maize production in CA systems. Nitrogen losses increase with the NAR and therefore greater application of N fertilizer would likely produce more negative environmental impacts. Maize yield, however, increases with NAR, together with stover and cover crop biomass, which results in an increased SOM level (Chapter 4) and perhaps better soil erosion control. Nitrogen fertilizer was also important for increasing carbon sequestration in water stable aggregates under oat winter cover crop. Carbon sequestration using winter cover crops may be a practical and cost effective mitigation strategy for climate change and there is merit in cropping systems that help sequester C in the face of climate change. Rate of application for N and P fertiliser may also influence soil C (Wang *et al.,* 2010). Therefore, SOM under winter cover crops could be considered in relation to N and P fertiliser application rates, in future similar studies.

Whilst the winter cover crops are a potential source of P and N (especially grazing vetch for N), mineralization can be out of sync with maize nutrional requirement since residues continue to decompose, at times when the crop does not require the N and P. Asychrony between crop residue mineralization and maize nutrient demand can result in undesirable cases such as: (i) too early N release from the winter cover crop residues to a young maize crop, favouring early weeds and N leaching or; (ii) late release resulting in early N deficiency. There is possibly room to improve N use efficiency, weed control and profitability through synchronization of residue N mineralization with maize crop. Research however, is required to look at strategies for improving the synchrony, such as manipulation maize planting dates and cover crop termination periods.

Plate 7.1 Grazing vetch mulch can offer soil fertility and weed control benefits to the maize crop (left) as opposed to the weedy winter fallow (right)

7.2 CONCLUSIONS

- Oat and grazing vetch winter cover crops significantly enhanced SOM, availability of some essential plant nutrients and maize yield. However, oat required fertilizer to achieve SOM benefits, while fertilizer was less important for grazing vetch.
- Targeting small doses of fertilizer to the winter cover crops as opposed to the maize crop gave higher biomass yield input, similar SOM response and grain yield, yet required less fertilizer investment.
- Both winter cover crops increased mineralizable SOM pools and labile P pools. Grazing vetch had an additional effect of increasing soil mineral N and maize nutrient uptake in the absence of fertilizer.
- Without fertilizer application, grazing vetch gave a higher marginal rate of return and thus profitability than the weedy fallow. It however lowered Mg availability and uptake by maize.

- In addition to SOM improvement, the winter cover crops hastened depletion of problematic weeds from seedbanks, leading to reduced weed pressure during maize growth. However, they allowed proliferation of some narrow leaf weeds such as *Cyperus esculentus* in the maize crop.

7.3 RECOMMENDATIONS

The following recommendations can be made from the results of this study:

- Oat and grazing vetch winter cover crops should be promoted as a means of improving soil fertility and reducing weed pressure in irrigated maize-based CA systems against weedy fallows
- Fertilizer use should also be encouraged as a means of maximizing biomass input, soil fertility and weed control benefits from the practice of winter cover cropping
- Nitrogen credits may be given to grazing vetch for reduction in N fertilizer required for optimizing yield whilst no additional N may be required in the oat system when compared with the weedy fallow.

Further research may be required to determine:

- The effects of the winter cover crops on soil physical properties that render a soils resistance to erosion, such as aggregate stability
- The effects of animal manures as an alternative fertilizer source for enhancing winter cover crop biomass and nutrient cycling
- The effects the winter cover crops on P recycling under continued practice, as well as soil C and nutrients through the entire rooting depth of maize (1 m)
- The effects of N and P fertilizer application rates on SOM under the winter cover crops

- Ways to deal with the weed ‘escapees’ such as *Cyperus esculentus* so that they do not become dominant problematic weeds in maize-winter cover crop rotations
- Strategies for improving the synchrony between residue nutrient mineralization and maize nutrient uptake in the maize-based CA systems.

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