MANAGING NUTRIENT INTERACTIONS FOR IMPROVED AGRONOMIC EFFICIENCY UNDER CONTRASTING SOIL CARBON LEVELS IN SMALLHOLDER FARMS

BY

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DECLARATION

I, **Natasha Tashinga Kurwakumire**, do hereby declare that this thesis is a result of original research work undertaken by myself except where clearly and specifically acknowledged. It is being submitted for the partial fulfilment of the degree of Master of Philosophy in Agriculture. It has not been submitted before for any degree or examination in any other University.

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ABSTRACT

Much of Sub –Saharan Africa is plagued by food insecurity due to low and variable soil fertility recurrent droughts and limited access to external inputs among other reasons. Variable levels of soil fertility caused result from diverse soil fertility management methods as well as parent materials of origin leading to inconsistent responses to fertilizer and manure, within and across fields and farms. It was hypothesised that soil organic carbon can be broadly used to define soil fertility domains for fertilizer use efficiencies. An analysis of the profitability of farmer management practices using a decision support tool, Nutrient Expert for Hybrid Maize (NE), was also carried out. Soil fertility was broadly categorised into three domains based on soil organic carbon (SOC) as an indicator of fertility as follows: field type1 ≤4 g C kg^{-1} soil, field type 2, >4–6 g C kg^{-1} soil and field type 3 >6 g C kg^{-1} soil. Nutrient omission experiments were set out to ascertain attainable yields, indigenous nutrient supplies and nutrient responses in Dendenyore ward, Hwedza district over two seasons, 2011/12 and 2012/13. The experimental design was a randomized complete block with plot sizes of 4.5 x 5 m^2 and three replicates. Data was analysed by GENSTAT 13 using analysis of variance (ANOVA) to examine site effects and treatment on maize productivity and site means were separated by Tukey's 95 % confidence interval. Treatments used were i) zero fertilizer control, ii) Nitrogen (N), Potassium (K), (iii) N, Phosphorus (P), Sulphur (S), iv), PKS and v) NPKS. Maize productivity was significantly influenced by nutrient management across all sites, with site mean yields on soils with >4g C kg^{-1} soil (Field types 2 and 3) ranging 3–3.2 t ha^{-1} significantly higher than for Field Type 1 which were less than 1 t ha^{-1}. Crop yield responses to N and P ranged from 1.2–2.35 t ha^{-1} and 0.71–2.10 t ha^{-1}, respectively with the highest responses on soils with >4g C kg^{-1} soil. Response to K was not significant. Across all sites indigenous N and P supplies were not enough to support a yield of one tonne of maize per ha without external nutrient input. The indigenous N supplies ranged from 8.5 kg to 27.6 kg N ha^{-1}, whilst indigenous P supplies were 2.2–11.7 kg P ha^{-1}. The second set of experiments involved applications of N, P, K and S alone or in combinations with manure, lime and micronutrients in a complete randomized block design with plot sizes 4.5 x 5 m^2 and three replicates. Data was analysed using GENSTAT 13 with site, treatment and year as fixed effects in a general ANOVA. Sole manure and a zero fertilizer control were the other treatments. Combinations of manure and fertilizer yielded the highest ranging from 2.67–5.55 t ha^{-1} across sites. Addition of sole manure on soil with <4 g C kg^{-1} did not increase yields significantly but on >4 g C kg^{-1} soil there was a significant increase to 2 t ha^{-1}. The liming effect was only evident on soil with <4 g C kg^{-1} soil at the most acidic site (4.4) with a significant yield gain of 0.9 t ha^{-1}. Addition of micronutrients (Zn, Bo and Mn) did not increase maize yields significantly. The use of a decision support tool to analyse common scenarios and soil fertility management practices across farmer resource endowment groups showed that there was room for increased productivity and profitability with improved nutrient management practices. The low resource endowment group had limited options for intensification as major financial constraints and limited access to external inputs hindered meaningful production. The variable response to fertilization across soil fertility domains indicated that, the best niches (>4g C kg^{-1} soil) must be targeted for application of fertilizers to increase productivity in smallholder farms. The hypothesis that SOC can be used as an indicator of soil fertility status was accepted. Analysis with NE clearly showed that socio-economic status and soil fertility management practices were linked thus soil fertility and resource endowment cannot be separated. Smallholder farmers must target the more fertile soils and build up soil fertility on the soils with <4 g C kg^{-1}.

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It is with a heart full of love and gratitude that I give thanks to my mother, son and brothers for believing in me and supporting me. Many thanks to my dear friends for being supportive.

I thank you Father in heaven who made it all possible!

DEDICATION

I dedicate this thesis to my mother Molly Kurwakumire. You are the embodiment of grace and kindness. I thank you for the vision to pursue my studies and all your support.

ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of variance
AEN	Agronomic efficiency of Nitrogen
AEP	Agronomic efficiency of Phosphorus
CEC	Cation exchange capacity
DST	Decision Support Tool
HRE	High resource endowment
ISFM	Integrated soil fertility management
LRE	Low resource endowment
LSD	Least significant difference
MRE	Medium resource endowment
NE	Nutrient Expert for Hybrid Maize
RE_N	Apparent nitrogen recovery efficiency
RE_P	Apparent phosphorus recovery efficiency
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Sub –Saharan Africa

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CHAPTER 1

INTRODUCTION

1.1 Background

Over 280 million people in sub –Saharan Africa (SSA) rely on subsistence farming and are largely food insecure (FAO, 2011). Agricultural production in the region is severely hindered by poverty, erratic rainfall and inherently infertile soils. Smallholder farmers constitute the majority of farmers in Zimbabwe and are estimated to be over a million. Most smallholder farms in Zimbabwe are on predominantly sandy soils which are inherently infertile (Grant, 1981; Mtambanengwe and Mapfumo, 2005). These soils have poor buffering capacity, low cation exchange capacity and are prone to nutrient leaching. Other than the macro- nutrients Nitrogen (N), Phosphorus (P) and Potassium (K), micro-nutrient deficiencies are also widespread as a result of long term nutrient mining through crop off-take without appropriate fertilizers being applied (Grant, 1981). This already dire situation is compounded by the large proportion of smallholder farmers that are resource-constrained and unable to purchase adequate mineral fertilizers. Solutions that target smallholder farmers to increase productivity remain highly relevant and critical if hunger is to be curbed.

In much of SSA many smallholder farming areas are characterized by marked short range spatial variability of soil fertility. This is as a result of localized inherent differences in parent material or different fertility management practices across farming units (Giller *et al.,* 2006; Wopereis *et al.,* 2006; Zingore *et al.,* 2007). Recognizing that soils are indeed variable is important for implementation of management strategies that enhance efficient use of scarce nutrient resources on smallholder farms. It is therefore worthwhile to consider the distinct capacity of different soils to supply nutrients to crops (Janssen *et al.,* 1990). When background soil characteristics or robust soil fertility indicators are known, it is possible to use them and appropriately tailor fertilizer application for improved nutrient use efficiency, thus ensuring that fertilizer interventions remain economically viable for smallholder farmers.

Livestock manure, cattle manure in particular has traditionally been used by farmers to fertilize their fields and maintain soil organic carbon, ensuring continued production of some yield (Swift *et al.,* 1994; Mugwira and Murwira, 1997). Due to past drought and disease outbreaks, the number of cattle has drastically reduced, with < 40% of households reportedly owning cattle (Murwira, 1993; Waeterloos *et al.,* 1993; Mapfumo, 1995). Some of the cattle owners have only one to four animals and such numbers cannot produce manure to fertilize large areas. Fertilization with mineral fertilizers is therefore, an option that can potentially be used by a wider spectrum of farmers, but there are major bottlenecks related to the high cost of mineral fertilizers, that are currently pegged between \$35 and \$40 for a 50 kg bag of ammonium nitrate (34.5 % N) and compound D (7 N-14 P_2O_5-7K_2O) fertilizer respectively.

1.2. Justification and Problem Statement

The wide variability in soil fertility on farms requires innovative strategies to enable continued sustainable crop production for poverty alleviation. Many studies have clearly documented the magnitude of nutrient gradients within and between farms in many parts of Africa including Zimbabwe (e.g. Mtambanengwe and Mapfumo, 2005; Tittonell *et al.,* 2006; Zingore *et al.,* 2007). The resultant spatial variability in soils on farms, largely due to differential nutrient management, has largely been overlooked when designing technological interventions in smallholder farming systems yet many researchers suggest that variability of soil fertility within farms poses a major challenge for efficient use of resources for increased crop productivity

(Wopereis *et al.,* 2006; Zingore *et al.,* 2007). Faced with inadequate nutrient inputs under erratic rain fed agricultural systems, prudent targeting of available nutrients on farms remains key to alleviating food insecurity (Giller *et al.,* 2006). An approach towards mitigating such concerns is more precise nutrient targeting based on initial soil fertility conditions. Soil organic carbon is such an indicator of soil fertility. This is in contrast to the current practices that are largely based on blanket fertilizer recommendations even when there are clear indicators of soil diversity recognizable to farmers.

While the majority of rural communities will continue to depend on agriculture to support livelihoods in the foreseeable future, the soil resource base has been compromised due to over 50 years of extractive farming practices, resulting in high crop yields becoming increasingly difficult to achieve. Research is therefore needed to generate unique and context specific solutions around identified problems related to soil fertility and fertilizer use in smallholder farms in Zimbabwe.

Recognizing that past management may have created pockets of fertility or infertility the study sought to generate empirical evidence on the magnitude of these contrasting islands and the associated responsiveness to external nutrient fertilizer resources, including organic amendments. Experimental programs with fertilizers and other nutrient resources in Zimbabwe have largely focused on N, P, K and Sulphur with little or no reference to micronutrients or secondary macronutrients e.g. calcium (Ca) and magnesium (Mg), yet these are essential to balanced nutrition. Response to micronutrients have been observed in Malawi, where yields improved by 40% after deficiencies of Boron (B), Zinc (Zn), S and K were removed through fertilizer application based on site specific soil sampling (Wendt *et al.,* 1993). It is also worthwhile to explore the benefits of Ca and Mg bearing liming materials on alleviating acidity that is prevalent in light textured soils that are prone to leaching of basic nutrients. Currently, liming materials are barely utilized by smallholder farmers in Zimbabwe.

Glaring contrasts have repeatedly emerged between crop productivity on smallholder farms and those from small experimental plots established by researchers and extension. With the use of integrated soil fertility management technologies, maize grain yields have ranged from 4-8 t ha^{-1} as compared to <0.8 t ha^{-1} in farmers' fields. This study seeks to generate knowledge that makes it feasible for farmers to achieve better harvests by judicious management of available resources.

1.3 Hypotheses

The study was hinged on three hypotheses as listed below.

1. Soil organic carbon can be broadly used to define domains for fertilizer use efficiencies on smallholder farms under different organic input resources
2. Application of lime or manure significantly influences N and P fertilizer use efficiency on sandy soils.
3. Application of micronutrients such as Zn, Bo and Mn on low C soils significantly improves N and P use efficiency

1.4 Objectives of the study

The general objective of the study was to improve targeting of nutrient resources by smallholder farmers in Zimbabwe by identifying SOC domains for enhanced crop productivity. The specific objectives of the study were to:

1. Determine N and P use efficiencies under different SOC levels
2. Determine maize yield response to N and P, fertilizers when applied with lime or manure on soils with different background organic carbon levels.
3. Evaluate the interactive effects of macro (N, P and K) and micronutrient (Zn, Bo, Mn) fertilization and maize productivity on soils differing in organic carbon levels
4. Investigate the profitability of soil fertility practises across resource endowment groups on smallholder farms

1.5 Thesis structure

Chapter 1 provides the background and justification of the study. Chapter 2 draws attention to relevant background material and the prevailing knowledge gaps. The study site, and general materials and methods employed in the study are presented in Chapter 3 while the more detailed and particular methodologies are in the respective results chapters. Determination of N and P use efficiencies was studied in Chapter 4. Chapter 5 then looks at the interactive effects of macro, micro-nutrients and manure with fertilizer across soil fertility gradients. The use of a decision support tool, Nutrient Expert for Hybrid Maize (NE) to assess the profitability of smallholder farmers' fertilizer management practices across resource endowment groups is examined in Chapter 6. Chapter 7 focuses on the major findings, conclusions and recommendations generated in the study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Many studies have demonstrated the influence of SOC on the quality of the soil. However research has shown that total SOC contents differ according to climate and soil types therefore thresholds and domains are diverse across the world (Baldock and Skjemstad, 1999). While research has been carried out in other parts of the world to define SOC contents into categories, the consensus has been that this categorisation must be context specific. Researchers have compared SOC in sandy soils to clay soils but studies across the predominantly sandy soils on Zimbabwean smallholder farms have not been carried out. This literature review delves into the background on soil fertility gradients, existing knowledge on SOC and its influence on soil fertility while highlighting knowledge gaps that this research may assist in bridging.

2.2 Soil fertility variability on smallholder farms

Spatial variability of soil properties, within or among agricultural fields is inherent in nature due to geologic and pedologic factors (Deckers, 2002) but variability on soils of similar texture is induced by the diverse management practices unique to each farmer. Normally, fields closest to the homesteads receive comparatively larger nutrient resources leading to the establishment of gradients of decreasing soil fertility from the homestead to distant fields (Carter and Murwira 1995; Tittonell *et al.,* 2006; Zingore *et al.,* 2007). This is as a result of labour constraints and security considerations which obviously leads farmers to concentrate nutrient resources on fields closest to the homestead. In some places the opposite has been evident whereby nutrient gradients of increasing fertility away from the homestead are evident such as in the central highlands of Ethiopia (Haileslassie *et al.,* 2007). The link between socio–economic status and soil fertility has been demonstrated in influencing soil fertility across farms. Studies have consistently shown that when farmers ranked their fields in terms of fertility, the higher resource groups had higher fertility than for the poorer farmers for the same category (Mtambanengwe and Mapfumo, 2005; Tittonell *et al.,* 2009). Richer farmers have access to manure as a result of livestock ownership and use more mineral fertilizers than their poor counterparts thus building up fertility on their farms.

Differential nutrient resource management at farm scale has been largely ignored when designing technological interventions in smallholder farming systems. For example, fertilizer recommendations used in Zimbabwe are blanket in nature and based on agro-ecological regions (Nyamangara *et al.,* 2000). However, studies have shown that gradients can be quite intense across a distance of only 100 m (Giller *et al.,* 2006). Recommended nutrient applications for total rainfall of >800 mm are 120 kg N ha^{-1}, 30 kg P ha^{-1} and 25 kg K ha^{-1} (Piha, 1993) . Research has clearly demonstrated that nutrient use efficiencies are not uniform across fields along soil fertility gradients thus necessitating interventions which can assist in characterising the best niches for fertilizer applications (Vanlauwe *et al.,* 2006; Zingore *et al.,* 2007; Tittonell *et al.,* 2008). Chikuvire *et al.* 2007, have recommended site specific management of niches such as termitaria soil and homestead environments but characterisation of soil fertility gradients according to soil organic carbon has not been studied.

2.3 Soil fertility management on Zimbabwean smallholder farms

Smallholder farmers employ a variety of methods and strategies to maintain and replenish soil fertility. The major setbacks in these endeavours in SSA are financial constraints that limit accessibility to mineral fertilizer (Sanginga and Woomer, 2009; Bekunda *et al.,* 2010), as well as poor and limited quantities of organic matter (Tanner and Mugwira, 1984).

2.3.2 Mineral fertilizer use on smallholder farms

The use of fertilizer remains well below the recommended rates with smallholder farmers only able to apply 10 - 50 % of the recommended rates (Mkhabela and Materechera, 2003). Lack of knowledge on correct fertilizer management practices is also quite extensive among smallholder farmers (Chuma *et al.,* 2000). Mineral fertilizers produced in Zimbabwe are mainly compound and straight fertilizers with no micronutrients. They supply the nutrients N, P and K mainly which are used in fertilizer recommendations ((Ahmed *et al.,* 1997). Rates of fertilizer actually used by farmers often vary greatly from blanket recommendations and have little or no relationship with the actual amounts and ratios of nutrients required to match the needs of the crop for high profitability and protection of the environment from leakage of excess nutrients (Buresh and Witt, 2007). Some research has even suggested that application rates higher than 60 kg ha^{-1} of N and 10 kg P ha^{-1} lead to dwindling returns on most soils (Zingore *et al.,* 2006). Unbalanced fertilizer use causes soil degradation as addition of N fertilizer without addition of other nutrients drives the removal of P and K which are not replenished through fertilizer inputs leading to their deficiencies. (Dobermann *et al.,* 2004).

Nutrient use efficiencies of N and P are widely variable across soil fertility gradients with efficiencies lower than 5 kg grain kg^{-1} N (Mushayi *et al.,* 1998) reported on some smallholder farms. Raising nutrient use efficiencies across smallholder farms by strategically targeting responsive fields is imperative when fertilizer is such a scarce commodity. Recovery efficiencies of as low as 0.1 kg kg^{-1} of P have been found in some fields which have multiple chronic nutrient deficiencies rendering the use of mineral fertilizers ineffective on such soils

(Chikowo *et al.,* 2010). Nutrient use efficiencies measured under practical farming conditions are mostly lower than those reported from research experiments but information on nutrient use efficiency in diverse cropping systems remains insufficient (Doberman and Cassman, 2002). Research has also shown that if farmers are to avoid nutrient losses through leaching or scorching of crops fertilization regimens must be flexible and responsive to rainfall patterns to counter such losses (Piha, 2003).

2.3.3 The role of cattle manure on smallholder farms

Integrated soil fertility management (ISFM) is the practice of utilising soil fertility management practices and adapting these to local conditions to maximise fertilizer and organic input use efficiency. Consequently in the Zimbabwean context, cattle manure plays a pivotal role as it is widely used as a soil amendment in smallholder farms (Zingore *et al.,* 2006). However the quality of cattle manure across smallholder farms remains poor due to poor nourishment of the cattle as well as poor handling and storage practices (Mugwira and Murwira, 1997). Cattle manure is largely a preserve of resource endowed farmers (Mtambanengwe and Mapfumo, 2005) but their application rates still fall well below the recommended rates of 37 t ha^{-1} once in every four years by the Alvord rotation (Alvord, 1936). The Alvord rotation from the 1940s recommended that in the communal lands, 37 t ha^{-1} manure must be applied to the first crop of maize in a four year rotation of maize- maize-legume- small grain. This recommendation does not factor in differences in soil fertility and fails to provide a spectrum of realistic amounts available to farmers. It is well known that cattle manure improves soil structure, bases and water holding capacity of the soil (Murwira *et al.,* 1995; Bationo *et al.,* 1998; Gandah *et al.,* 2003;) but the responses across soil fertility gradients have not really been quantified and studied. Cases of very low and at times even negative nitrogen recovery efficiencies have been recorded on application of poor quality manure due to immobilization effects (Chikowo *et al.,* 2010). Interventions to improve nutrient targeting against a background of farmer heterogeneity remain of utmost importance (Tittonell and Giller, 2013).

Cattle manure is rich in Ca, Mg and micronutrients such as Zn thereby ameliorating acidity and alleviating micronutrient deficiencies common on Zimbabwean smallholder farms (Prasad and Sinha, 1982). Studies have shown that on sandy soils, soil organic matter supplies most of the cation exchange capacity and buffering capacity on such soils thus the importance of studying dynamics of manure additions on sandy soils is extremely important (Mapfumo and Giller, 2001).

2.3.4 Woodland/leaf litter as a soil fertility ameliorant on smallholder farms

Farmers who do not own cattle and are classified as resource constrained make use of woodland and leaf litter as an organic amendment (Nyathi and Campbell, 1993). Findings on quality of leaf litter are varied, with Young (1989) describing leaf litter as a good quality organic amendment. However, commonly used Miombo litter has been found to release N slowly in the short term (Nyamangara *et al.,* 2009). Woodland litter has a mulching effect and improves water holding capacity of the soil. Findings by Manzeke et al. (2012) have shown P to be very low in leaf litter but with comparable amounts of N to manure. The use of woodland/leaf litter has been curtailed by deforestation which is rampant in the rural areas (Nyathi and Campbell, 1993).

2.3.5 Liming and acidity on smallholder farms

Soil acidity is one of the main hindrances to maize production in the smallholder areas of Zimbabwe (Grant, 1971) with increases of soil acidity also being reported due to reduced usage of manure, lack of liming, use of mineral fertilizers as well as leaching of the predominantly sandy soils (Grant, 1981; Nyamangara and Mpofu, 1996). However, studies have not really quantified the effects of lime on soils with contrasting carbon levels and different moisture levels (Mapfumo and Mtambanengwe, 2004). Studies to systematically assess the levels of soil acidity are lacking as blanket recommendations are given out to farmers without any soil analysis whatsoever. Extension services recommend 150 kg ha^{-1} and 250 kg ha^{-1} of $CaCO_3$ on sandy soils and clay soils respectively for every 0.1 difference below the required pH (Dhliwayo *et al.,* 1998). Grant (1981) argued that liming of smallholder farming areas was not a priority as smallholder farmers did not use much mineral fertilizers and their use of manure would also ameliorate soil acidity. However, surveys by the Department of Research and Specialist Services of 3000 fields showed that soil acidity is one of the greatest hindrances for maximum crop productivity (Dhliwayo *et al.,* 1998). This study sought to quantify the effects of liming on maize yields and soil properties such as pH and base nutrients on soils with contrasting carbon levels as this area has not really been studied.

2.4 Soil organic carbon as an indicator of soil fertility

Soil organic carbon is a fundamental component of soil quality indicators (Loveland and Webb, 2003). The positive relationship between increasing quantities of SOC and enhanced crop nutrition, soil structure and water holding capacity of the soil has been elucidated by many researchers (Chivenge *et al.,* 2007; Lal, 2006; Rusinamhodzi *et al.,* 2013). Research by Mtambanengwe and Mapfumo, (2005) has clearly shown the need to maintain SOC at levels that are conducive to the application of mineral fertilizers. However, knowledge of such carbon thresholds remains unclear across the region with studies few and far between. In a study in Zimbabwe spanning over 100 farms the critical threshold for response to fertilizers by maize was deemed 4.6 g C kg soil (Mapfumo, 2006) but in some places in the region responses to fertilizers have been elicited at much lower carbon levels (Bationo *et al.,* 1998).

Texture is intrinsically linked to SOC content and of fundamental importance for the establishment of SOC thresholds for N management (Msunguzi *et al.,* 2013). However, SOC is not the only determinant of these responses as other factors including rainfall and temperature affect nutrient use efficiencies (Dick and Gregorich, 2004). Few studies have quantified water productivity across soil organic domains and this study seeks to shed light on this relationship. Sandy soils have a low capacity to protect soil organic matter thus SOC is lower than on clay soils and thresholds differ as a result. The recognition of SOC by smallholder farmers as fundamental to soil fertility has been shown by their cognisance of soil colour as a determinant of soil fertility (Barrios *et al.,* 2001; Hossain, 2001). The darker the soil, the more organic matter it contains and hence the greater the fertility.

2.5 Soil nutrient status in Zimbabwean smallholder farms

Smallholder farmers battle with inherently infertile soils while exhausting an already depleted and fragile nutrient base (Grant, 1981). Soil fertility is one of the factors most limiting production and Rurinda *et al*. (2013) indicate that soil fertility management can mitigate food insecurity during a drought year. Poor responses to fertilizers are rife on smallholder soils and in the most extreme cases no response to fertilizer can be elicited on some soils and these are termed "non –responsive soils" (Kho, 2000; Zingore *et al.,* 2007). Zimbabwean smallholder soils are mainly coarse textured and sandy, with low levels of SOC. Water holding capacity on such soils is low. The soils have poor buffering capacity and a low cation exchange capacity ranging between 1 and 6 $cmol_c\ kg^{-1}$, which is attributable to the small amounts of predominantly 1:1 kaolinitic clays (Nyamapfene, 1991).

Soils in Zimbabwe generally have low micronutrient concentrations (Tagwira, 1993). The problem of micronutrient deficiencies has escalated over the years to a significant level because of nutrient mining cropping practices on already poor soils. In Malawi, chronic deficiencies of major macronutrients as well as micronutrients (Zn and B) have been reported on most soils and the micronutrients have been classified as limiting (Matabwa and Wendt, 1993). On application of Zn and B, yields increased by 40 % in some places (Wendt *et al.,* 1993). Concerns from many years back by Kang and Osiname (1985) on the lack of systematic studies on micronutrients have still not been addressed over the past decades with no studies that categorically address responses to micronutrients on soil fertility gradients.

Total zinc in soils varies from 10-300 ppm and a soil is considered deficient at less than 0.6 ppm (Alloway, 2004). Zinc can be blended with macronutrients to reduce costs (Katyal and Rhandawa, 1983). However, high production costs of Zn fertilizer have led to its unavailability (Manzeke *et al.,* 2012). High P levels have been shown to cause Zn deficiency due to formation of insoluble phosphate (Katyal and Rhandawa, 1983). Zinc deficiency is noticed in highly alkaline soils but in Zimbabwe the deficiency is inherent, hence its prevalence on even acidic soils (Grant, 1981).

2.6 Decision support tools for smallholder farmers

Farmers make decisions continually about the scale of production and operations at the farm based on socio-economic realities on the ground. Issues like, where and how to target nutrients can be made easier by the use of decision support tools (DST's). Decision support tools can be defined as a computer based system supporting the decision making process (Finlay, 1994). To ensure that relevant outcomes are produced from the tools the decisions must be approached in the way farmers approach the problems and not necessarily from the researcher's point of view.

Site specific recommendations are often expensive and time consuming to come up with through experimentation hence DST's provide a quicker alternative to generate such data. Decision support tools such as the Nutrient Expert and the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) can be employed to make decisions about fertilizer recommendations for the particular soil. However the uptake of DST's has remained slow due to complex data requirements which make the tools difficult to use (Bontkes and Wopereis, 2003). Traditional methods of addressing soil fertility problems may need to be overhauled making way for technologies such as DSTs that are cheaper and can assist in the battle to curb hunger in SSA.

2.7 Approaches to site specific fertilizer recommendations

Site specific nutrient management (SSNM) provides an approach for managing a specific crop by making sure the crop gets the right amount of nutrients as and when needed. The concept of SSNM was developed in the mid-1990s and refined on 200 farms over a period of 3 years in Asia where 90% of the world's rice is produced on irrigated farms (Dobermann *et al.,* 2004). The most important step towards calibration of site specific fertilizer requirements is the estimation of the indigenous nutrient supplies, which is the cumulative amount of a nutrient from all indigenous sources (Sen and Majumdar, 2006). Rates of fertilizer actually used by farmers often vary greatly from blanket recommendations and have little or no relationship with the actual amounts and ratios of nutrients required to match the needs of the crop for high profitability and protection of the environment from leakage of excess nutrients (Buresh and Witt, 2007). Unbalanced fertilizer use causes soil degradation as addition of N fertilizer without addition of other nutrients causes soil degradation through removal of P and K (Dobermann *et al.,* 2004). Soil testing is an important tool for preparing site specific fertilizer recommendations but seldom used by farmers due to lack of supportive research, cost of soil analysis and limited capacity for soil testing at the local level (Dhliwayo *et al.,* 1998).

In Thailand rapid soil test kits were developed for rapid analysis of soil pH, N P and K (Attanandana *et al.,* 2007). This therefore made precision farming faster and easier as less time was spent on soil testing. In Africa, precision farming is still a pipedream but a more targeted approach on where best to invest nutrient resources is of utmost importance in light of heterogeneity across farmers' fields. Site specific nutrient management provides an approach that utilizes detailed knowledge of nutrient distribution or some other easily recognizable proxy for soil fertility. This study therefore sought to investigate the response of maize to mineral fertilizers across soil fertility domains to generate knowledge on the associated nutrient efficiencies across similar agro-ecologies.

CHAPTER 3

GENERAL MATERIALS AND METHODS

3.1 Site description

The study was conducted on smallholder farms in Dendenyore ward (18°15' latitude, 32°22' longitude), Hwedza district, in Eastern Zimbabwe (Figure 3.1), during the 2011/12 and 2012/13 cropping seasons.

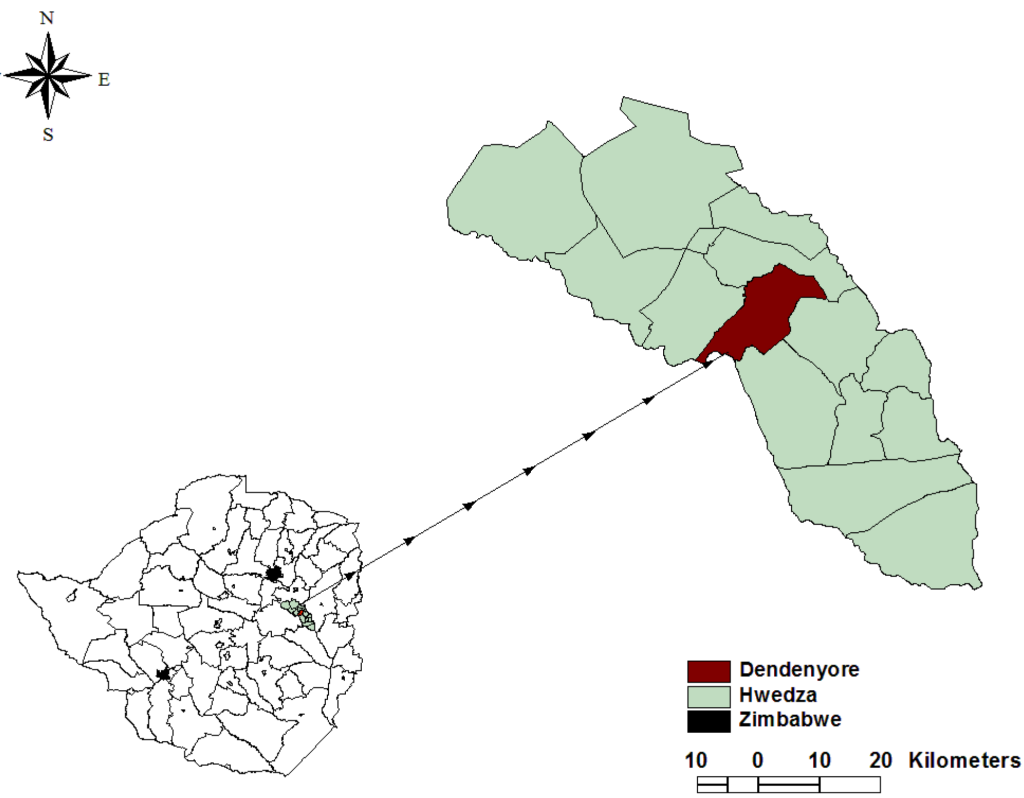

Figure 3.1 Map of the study area in Dendenyore Ward, Hwedza District, Zimbabwe

The research site lies in Natural Region (NR) II receiving >800 mm annual precipitation between November and March. Zimbabwe is delineated into five agro-ecological regions with NR I having the most reliable rainfall of >1000 mm per cropping season while NR V is semi-arid with long-term average annual rainfall of <500 mm (Vincent and Thomas, 1960). Hwedza is known to have a high inter-annual rainfall variability with a coefficient of variation of between 23%- 40% (Mazvimavi, 2010). The area has a mean temperature of 24°C during the cropping season, between November and April. Soils are predominantly sandy Lixisols with low SOC and inherently poor nutrient supply potential.

The farming system is characterized by individual household ownership of between 1-5 hectares of arable fields, with communal grazing in designated areas. Maize is the main staple cereal crop, with grain legumes such as groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* [L.] Walp) being important as well. There is a strong crop-livestock interaction, as cattle are fed on crop residues when pastures are scarce during the dry season, and they in turn provide manure that is used to fertilize cropped lands. Soil fertility variability within and among farms is a strong feature, largely due to differences in crop and nutrient management practices by differently resource-endowed farmers (Mtambanengwe and Mapfumo, 2005; Zingore et al. 2007). Variation of parent materials from which the soils are derived and landscape position also define soil fertility status and productivity potential.

3.2 Materials and Methods

Detailed methodologies for each data chapter are found in Chapters 4, 5 and 6, respectively. General procedures and laboratory protocols used in the study are described below.

3.2.1 Field sites selection procedure and experimental design

An exploratory survey was carried out by randomly selecting 60 fields from farming households in the study area, within a radius of 5 km. For each of the selected fields, five soil samples were taken on a diagonal transect of the field, at a depth of 0-20 cm, and bulked to form one composite sample. The top 0-20 cm soil layer is considered as the plough depth achieved by farmers using ox-drawn ploughs. Subsequently, a sub-sample of the soil was taken for laboratory analysis. These samples were analyzed for soil organic carbon (SOC) and texture, using the modified Walkley- Black and hydrometer methods, respectively. The fields were subsequently divided into three soil fertility domains based on SOC, using modified guidelines adapted from Zingore et al. (2011). The lower threshold was modified to ≤4 g C kg-1 soil instead of ≤ 4.6 g C kg soil.

- Field Type 1: fields with ≤4 g C kg^{-1} soil – fields that have been poorly managed and have history of poor yields. The clay contents of such fields rarely exceed 10%
- Field Type 2: fields with >4-6 g C kg^{-1} soil, often being fields that have received organic amendments intermittently. Clay content (10-15%) substantially overlaps with Field Type 1(≤4 g C kg^{-1} soil)
- Field Type 3: fields with >6 g C kg^{-1} soil, these are few fields that have a history of good management, including use of organic manures and mineral fertilizers, and had clay content generally >15%

Six experimental sites were then strategically selected, targeting these three field types on the same landscape and within a 1 km radius. During the first season each field type had two sites and in the second season these were reduced to one site per field type to minimise confounding effects due to rainfall. To determine nitrogen and phosphorus use efficiencies a nutrient omission experiment was set up with three replicates in a complete randomized block design. This enabled determination of the degree of limitation of each nutrient and estimation of indigenous nutrient supply. The second experiment in a complete randomized block design was to determine the interactive effects of macro and micronutrient fertilization with the use of lime or manure. This enabled determination of other factors limiting yield besides the macronutrients as micronutrients and base nutrients have been documented as limiting. For both experiments individual plot sizes were 4.5 x 5 m^2. The test crop was maize with the SC 513 maize variety planted at a spacing of 0.9 m inter-row spacing and 0.25 m intra-row spacing. During the second season only three out of the six sites were used to eliminate possible confounding effects due to rainfall. Close proximity of the contrasting field sites was deemed necessary to eliminate possible confounding effects due to differences in rainfall as spatial variability in rainfall is known to be high. Yield data and soil samples were collected from the experimental sites. For the nutrient omission experiment data was analysed using analysis of variance (ANOVA) with GENSTAT 14 statistical package. Site means were separated using Tukey's 95 % confidence interval. The second set of experiments with macro and micronutrients was analysed by GENSTAT 14 statistical package with site, treatment and year as fixed effects. Where appropriate LSDs were used to separate means at $P < 0.05$.

3.3 Characterization of soils for experimental sites

Before experiments were established in November 2011, a composite soil sample, 0-20 cm depth, from 10 randomly selected points within each of the six experimental fields was collected for detailed soil characterization. The methods described below were employed in soil analysis.

3.3.1 Total soil organic carbon determination

Soil organic carbon was determined by a modified Walkley –Black method (Anderson and Ingram, 1993). The soil was sieved through a 2mm sieve and 1 g was weighed in a digestion flask. Thereafter 2 ml of distilled water was added to the soil. To oxidise the carbon 10 ml of 5% potassium dichromate solution was added to completely wet the soil. Twenty ml of sulphuric acid was added to the mixture using a calibrated burette and gently mixed by swirling. The mixture was digested for 30 minutes then allowed to cool. A 50 ml 0.4 % solution of barium chloride was added then mixed thoroughly by swirling. The resultant mixture was then brought to the 100 ml mark and left over night to leave a supernatant solution. An aliquot of the supernatant solution was transferred into a colorimeter cuvette and absorbance of the standards, sample and blank were measured with a BUCK Scientific 100 VIS spectrophotometer. Thereafter a graph of absorbance at 600 nm was plotted against a set of standards. The standards were prepared by dissolving 11.886 g dry sucrose in 100 ml of distilled water to make up a stock solution of 50g/ml carbon. A pipette was then used to transfer 0, 5, 10, 15, 20 and 25 ml of the 50 g/ml C stock solution and made up to the mark in the respective volumetric flasks. A pipette was used to transfer 2 ml of the above mentioned standards into 100 ml digestion tubes and heated to dryness. This resulted in dried contents of 0, 5, 10, 15, 20, 25 mg C. These were then made up to the mark with distilled water to result in a standard series of 0, 0.05, 0.15, 0.20, and 0.25 mg C/ ml. The % organic C was calculated as follows:

% organic C = (a-b) x 0.1)/ W

Where a = Cr^{+3} ions in the blank, b = Cr^{+3} ions in the sample and W = the weight of the soil.

3.3.2 Soil pH and texture determination

Soil pH was determined using the H_2O method (Okalebo *et al.,* 2002). The inverse log of the hydrogen ion concentration is the pH of the soil sample. The pH was measured in a 2.5:1 of water to soil suspension. To a soil sample weighing 10 g, 25 ml of deionised H_2O was added. The mixture was shaken on a mechanical shaker for 30 minutes and thereafter a pH value was obtained from the suspension. The hydrometer method (Gee and Bauder, 1986) was used to determine soil texture. A soil sample weighing 100 g was weighed into a 400 ml beaker and 10 ml of 5 % sodium hexametaphosphate was added to the sample. The soil was then saturated with distilled water and left to stand overnight. The mixture was shaken on a mechanical shaker for exactly four and half minutes and after mixing, a hydrometer was inserted into the mixture. A temperature reading was obtained after 40 seconds and thereafter the mixture was left to stand for five hours and readings from the hydrometer and thermometer were obtained. The percentage of silt and clay was calculated and the textural class for the sand was obtained from a textural triangle.

Calculations:

40 seconds (correctional reading) = 2 (40 seconds reading – 40 seconds blank + T)

5 hours (correctional reading) 2 (5 hours reading – 5 hours blank + T)

Where T = temperature corrections: For every degree above 20 °C (d), T = 0.3 x d for every °C below 20 °C (d); T = - 0.3 x d

d = Temperature difference

% sand = 100-40 seconds (correctional reading)

% silt = 40 seconds (correctional reading) – 5 hours (correctional reading)

% clay = 5 hours (correctional reading)

3.3.3 Determination of total N in soil

The micro- Kjedahl method (Anderson and Ingram, 1993) was used to determine total N. The content of total N was measured in a digest obtained by treating soil samples with a digestion mixture made up of hydrogen peroxide (H_2O_2), sulphuric acid H_2SO_4 and lithium sulphate (Li_2SO_4). Selenium powder was used as a catalyst. To a sample of air dried soil (0.5 g) in a digestion tube, 4.4 ml digestion mixture was added. The mixture was then digested at 360° C for 2 hours. After cooling the solution 100 ml of distilled water was added by first adding 25 ml and the remainder added afterwards. The mixture was allowed to settle so a clear solution could be taken from the top of the tube for analysis. Colorimetric determination of total N in the soil was subsequently carried out. A micro-pipette was used to put 0.1 ml of the standards and samples into suitably labelled test tubes. A reagent containing 34 g sodium salicylate, 25 g trisodium citrate and 25 g potassium tartrate and made up to 100 ml of distilled water was added to each test tube. The mixtures were mixed well and left for 15 minutes. A second reagent made of sodium hydroxide and sodium hypochlorite was added into each test tube and left for an hour for colour development. Standards containing 0, 2.5, 5.0, 7.5, 10.0 and 15.0 mg N / litre were made from the digestion mixture. Graphs of absorbance (655 nm) were then plotted against standard concentration. The % N was calculated as follows:

% N = {(absorbance of sample – absorbance of blank) x F x 0.01}/ sample weight

Where F = the mean of (concentration of standards (ppm)/ absorbance of standards

3.3.4 Determination of available P

The Olsen method was used to obtain available P in the soil. An extracting solution made up of 0.5 M sodium bicarbonate at pH 8.5 was added to soil weighing 2.5 g in a plastic bottle. The mixture was shaken for 30 minutes and thereafter the suspension was filtered through Whatman No. 42 paper. The filtrate was used for colorimetric P measurements. This was carried out by adding 5 ml of boric acid and 10 ml of ascorbic acid and standing for an hour. Colorimetric determination from the formed phosphorus molybdate complex was then carried out at 880 nm.

$$P\ (mg\ kg^{-1}) = \frac{(a-b) \times V \times F \times 1000}{1000 \times W}$$

Where a = the concentration of P in the sample; b = the concentration of P in the blank; V= volume of extracting solution; F= dilution factor; W= weight of soil.

3.3.5 Determination of total exchangeable bases

A soil sample weighing 10 g was extracted with an excess of 1M Ammonium acetate. The NH_4^+ ion displaces the exchangeable cations from the soil into the resulting leachate. The amounts of exchangeable K, Ca and Mg in the leachate were determined by flame photometry (K) at 766.5 nm and atomic absorption spectrophotometry at 422.7 nm and 285.2 nm for Ca^{2+} and Mg^{2+} respectively. Lanthanum and strontium were added as a releasing agent to prevent formation of refractory compounds e.g. phosphates, which may interfere with the determination. The total exchangeable bases were calculated as follows:

$$Mg\ kg^{-1}\ K,\ Ca\ and\ Mg = \{(a-b)*v * f * 1000\}/\ (1000 * w)\}$$

where "*a*" is the concentration of K, Mg and Ca in the sample, "*b*" is the concentration of element in blank sample, v is volume of the extract solution, w is weight of the soil sample and f is the dilution factor.

3.4 Plant tissue analysis

At physiological maturity, 14 maize plants were harvested from net plots of 2 central rows by 2m long (3.6 m^2). The cobs were sun dried in perforated harvesting bags over 10 days, shelled and grain yield determined using a digital scale. The grain moisture content was then determined and averaged for three sub-samples per plot using a John Deere SW moisture meter. Maize yields were reported at 12.5% moisture content, the standard moisture content for maize marketed in Southern Africa. Maize stover for each net plot was weighed in the field using an Adams digital field scale and sub-samples were taken to the laboratory for further drying and moisture correction. These were then separately analysed for total N, P and K content using standard hot acid extraction methods (Okalebo, 2002). Total nutrient uptakes were determined by multiplying the respective nutrient concentrations in grain and the grain yield.

3.4.1 Determination of N in grain and stover

The Total Kjedahl Nitrogen (TKN) method was used to determine plant N and it is based on the wet oxidation of organic material using H_2SO_4 and a catalyst whereby organic N is converted to ammonium ions (Okalebo *et al.,* 2002). Nutrient uptake in grain was determined, by taking sub- samples of shelled dry grain from the respective plots and grinding the grain to pass a 2 mm sieve. For stover samples the same procedures employed for the grain analysis were carried out. All plant samples were dried at 70°C with moisture levels between 1-2% to prevent the loss of nitrates by a sudden reaction with sulphuric acid which would underestimate N levels. To one gram of plant material 10 ml sulphuric acid (H_2SO_4) was added in the presence of $CuSO_4$ - Se as a catalyst. The H_2SO_4 acid completed digestion at high temperatures. The mixture was then heated to form a colourless solution. The mixture was then transferred to a distillation flask where 50 % sodium hydroxide and dilute H_2SO_4 were added. The distillate from steam distillation was mixed with boric acid to produce ammonia gas which was trapped in a flask and titrated against dilute sulphuric acid using thymol blue as an indicator. The end point was determined by change of colour in the mixture from blue to pink. Colorimetric determination of N using a BUCK Scientific 100 VIS spectrophotometer at 650 nm was then carried out. The nitrogen concentration in the sample material expressed in % N was calculated as follows:

$$N\,\% = \frac{(a-b) \times v \times 100}{1000 \times w \times al \times 1000}$$

Where a = concentration of N in the solution, b = concentration of N in the blank, v = total volume at the end of the analysis procedure, w = weight of the dried sample and al = aliquot of the solution taken.

3.4.2 Determination of plant P

The principle for determination of plant P is based on the wet oxidation of organic P using perchloric acid ($HClO_4$) (Isaac and Johnson, 1985). A plant sample weighing one gram was saturated with calcium acetate and ashed in a muffle furnace at 600°C. Thereafter perchloric acid was added to the plant sample and the mixture was placed in a water bath for 30 minutes. The mixture was then put in a volumetric flask and made up to the mark with distilled water. The solution was read at 400 nm using a Varian Spectra AA 50 spectrophotometer after adding vanadomolybdate reagent to enable colour development. The amount of phosphorus present in the solution was read off a calibration curve. The P in the sample was calculated as follows

$$P \text{ in sample } (\%) = \frac{c \times v \times f}{W}$$

Where c = corrected concentration of P in the sample, v = volume of the digest, f = dilution factor, w = weight of the sample.

3.4.3 Determination of K, Zn in plant tissue

Potassium and Zn were determined in HCl extracts by flame emission spectrometry by atomic absorption spectrometry (Reuther, 1965). Plant samples were ashed at 500˚C in a furnace overnight. After cooling the samples to room temperature, six drops of concentrated nitric acid together with 6 ml of 25 % HCl were then added to the plant material. The samples were dried under ultra violet light to allow oxidation to take place. The sample was cooled for half an hour and a further 6 ml of HCl was added to the cooled mixture. This mixture was made to the mark in a 50 ml volumetric flask with distilled water after filtering. An atomic absorption spectrophotometer was used to read the absorbencies of K and Zn at 766.5 nm and 213 nm, respectively. Calculations were carried out as follows:

For example:

Concentration of Zn in extract = C_{Zn}

Total no of μg Zn extracted = C_{Zn} X 50

CHAPTER 4

MAIZE PRODUCTIVITY, NUTRIENT AND WATER USE EFFICIENCIES ACROSS SOIL FERTILITY DOMAINS ON SMALLHOLDER FARMS IN HWEDZA, ZIMBABWE

Abstract

Strategic targeting of scarce nutrient resources by smallholder farmers on different field types has remained poor partly due to knowledge limitations, resulting in inefficient use of the resources. The aim of the study was to establish efficient strategies for use of nutrient resources so as to narrow the yield gap in maize production on heterogeneous light-textured soils under rain-fed conditions in east central Zimbabwe. A nutrient omission study in a complete randomized block design was implemented during two cropping seasons, across six on-farm sites with soil organic carbon (SOC) ranging from 3.5–8.9 g kg^{-1}, and clay content between 4–19%. Treatments used were: i) zero fertilizer control, ii) NK, iii) NPS, iv) PKS, and v) NPKS. Rainfall water productivity, RWP, (kg grain mm^{-1}) was used as a proxy for water use efficiency for the different nutrient combinations. During both seasons, only 70 kg ha^{-1} N could be applied across all sites as prolonged mid-season droughts forced withholding of the second N topdressing targeted at maize anthesis. Data was analysed using GENSTAT version 13 statistical package using analysis of variance (ANOVA) and site means were separated by Tukeys 95 % confidence interval. Maize productivity was influenced by both nutrient management and initial soil fertility. During the first season, maize yields across sites ranged from 0.25–0.84 t ha^{-1} for the control and 2.05—3.75 t ha^{-1} for the NPKS treatment that represented attainable yields. The corresponding RWP were 0.38–1.13 kg grain mm^{-1} for the control and 3.15–7.66 kg grain mm^{-1} for the NPKS treatment. For the second season, maize yields for the control were 0.2–1.2 t ha^{-1}, while those for the NPKS treatments ranged from 2.4–3.60 t ha^{-1}. Across sites, response to N was 1.2–2.35 t ha^{-1}, response to P was 0.71–2.10 t ha^{-1} and response to K ranged 0.08–0.30 t ha^{-1}, indicating little response to K. Overall, balanced nutrient management has an overriding effect on maize grain and water productivity, but only for soils with SOC > 4 g kg^{-1}soil. Nitrogen and P remain the most limiting nutrients. In contrast, addition of K did not enhance grain yield, or influence response to N or P.

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4.1 Introduction

Smallholder farmers in sub-Saharan Africa (SSA) face challenges that include inherently poor soil fertility, limited access to external inputs and recurrent droughts. Crop production is largely dependent on natural rainfall that is characterized by poor distribution, with flooding and drought episodes occasionally occurring within a cropping season (Mtambanengwe *et al.,* 2012). Consequently, a paltry 20-40% of the seasonal rainfall is used productively due to the mismatch between soil water availability and crop demand, compounded by high runoff and evaporation losses (Falkenmark and Rockstrom, 2005; Nyagumbo and Rurinda, 2007). A combination of poor nutrient and soil water availability has resulted in maize productivity rarely exceeding 1.5 t ha^{-1} on the majority of the smallholder farms. The green revolutions in Asia and Latin America were underpinned by high rates of mineral fertilizer application and improved seed varieties (e.g. FAO, 1996). However, in SSA, fertilizer use is still less than 10 kg ha^{-1}largely due to prohibitive prices (Camara and Heinemann, 2006), and general inaccessibility. This falls well below the fertilizer use target of 50 kg ha^{-1}, deemed a prerequisite for an African Green Revolutionby the Abuja Declaration (Africa Fertilizer Summit, 2007).

Many smallholder farms are known to be spatially heterogeneous in terms of soil quality, mainly due to differences in management of fields within or across farms (Prudencio, 1993; Manlay *et al.,* 2002; Masvaya *et al.,* 2010). Differences in nutrient resource management by farmers, which is usually a function of resource endowment and preferential application of nutrient inputs to fields close to the homesteads, has often accentuated variability in soil fertility, creating gradients of fertility across fields and farms (Mtambanengwe and Mapfumo, 2005; Zingore *et al.,* 2007). Short range spatial variability in soils also exists within and across farms due to inherent properties of soils. It has also been established that nutrient use efficiencies and crop yields vary strongly along gradients of soil fertility within smallholder farms (Vanlauwe *et al.,* 2006; Vanlauwe *et al.,* 2011). Thus, targeting nutrient resources tactfully to enhance nutrient use efficiencies are basic principles that should be used by resource -constrained farmers. Some soils have complex chemical imbalances and poor physical structure that inhibit crop production even if adequate fertilizers are used, a phenomenon that is now referred to as 'poorly or non-responsive' soils' (Vanlauwe *et al.,* 2002; 2011; Tittonell *et al.,* 2007; Zingore *et al.,* 2007). Despite the highly variable soil fertility conditions, fertilizer recommendations currently available to smallholder farmers rarely reflect these circumstances and are based on an assumption of soil resource base homogeneity (Snapp *et al.,* 2003). For example, in Zimbabwe fertilizer recommendations are linked to agro-ecological zones that are principally delineated based on rainfall, despite well-established variability in soils over short distances within the agro-ecological zones (Ncube *et al.,* 2007; Zingore *et al.,* 2007).

Spatial variability in soils on smallholder farms has largely been trivialized when designing technological interventions, yet it is widely asserted that variability of soil fertility within farms poses a major challenge for efficient use of resources for increased crop productivity (Tittonell *et al.,* 2007; Wopereis *et al.,* 2006; Zingore *et al.,* 2007). Smallholder farmers do however have local indicators of soil fertility which include soil colour, texture, and dominant weed species as determinants of soil fertility. However, research by Chikuvire *et al.,* 2007 has shown that farmers' perceptions were not accurate as they were more likely to invest less fertilizer or no resources on termitaria leading to nutrient mining and no added advantage. Explicitly recognizing that farmers deal with a variable soil resource base is important for the formulation of nutrient management strategies that enhance efficient use of nutrient resources on farms (Janssen *et al.,* 1990). Considering that fertilizer resources are scarce, it is critical that fertilization regimes be tailored to both the site specific biophysical environments and socio-economic status of farmers. When robust soil fertility indicators are known, it is possible to use them to tailor fertilizer application strategies for an informed approach that could lead to improved farming system functioning (Janssen *et al.,* 1990; Zingore *et al.,* 2007; Nandwa, 2001). Soil organic carbon (SOC) is one such robust indicator for soil fertility status that can be used to predict resource use efficiencies under a range of management regimes. Soil organic carbon and pH have already been integrated in the model Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) as useful parameters for informing soil productivity (Janssen et al. 1990).

One of the strategies that are employed by farmers in maintaining or improving SOC is the application of organic materials, such as livestock manure and composted material. However, use of livestock manure in crop fields is largely a preserve of farmers who own cattle, as farmers who only have small ruminants such as goats, do not get sufficient manure to fertilize both crops fields and vegetable gardens, for which the latter is prioritized. Appropriate use of mineral fertilizers is a potential alternative strategy to enhance primary crop productivity, fixing atmospheric carbon and generating organic residues that when incorporated into the soil can increase soil SOC inputs, and support sustainable crop production intensification. However, most of these residues are eaten by livestock during the dry season, save for the below-ground root biomass inputs, making this pathway ineffective in communities with high livestock populations. The specific objectives of this study were (i) to define soil fertility domains relevant for the development of nutrient management recommendations according to SOC levels, (ii) to determine attainable yields and indigenous nutrient (N, P, K) supply for soil fertility domains, and (iii) to establish the N, P, K and water use efficiencies across soil fertility domains within a landscape.

4.2 Materials and methods

4.2.1 The study area

The study was carried out in Dendenyore ward, a smallholder farming community in Hwedza district (18°41S', 31°42E'), central eastern Zimbabwe during the 2011/12 (Year1) and 2012/13(Year 2) cropping seasons. Details of the study site are given in section 3.1.

4.2.2 Field sites selection procedure

The detailed methodology for selection of field sites is found in section 3.2.1 and field types were classified as follows:

- Field Type 1: fields with ≤4 g C kg^{-1} soil
- Field Type 2: fields with 4-6 g C kg^{-1} soil
- Field Type 3: fields with >6 g C kg^{-1}

Within each of these three field type domains, two field sites were identified for experimentation during the 2011/12 cropping season, for a total of six sites (Table 4.1). During the second year, only three of the six original sites were retained, strategically targeting three fields on the same landscape (within a 1 km radius), but still representing the three field type domains. This strategic decision was done to eliminate possible confounding effects due to differences in rainfall as spatial variability in rainfall is also known to be high within short distances. Plot sizes were 4.5 x 5 m^2 and the experimental design was a complete randomized block design.

4.2.3 Characterization of soils for experimental site

Before experiments were established in November 2011, a composite soil sample, 0-20 cm depth, from 10 randomly selected points within each of the six experimental fields was collected for detailed soil characterization. Total nitrogen (N) and available phosphorus (P) were analyzed using the micro-Kjeldahl method and the modified Olsen method, respectively (Anderson and Ingram, 1993). Exchangeable bases (K, Mg and Ca) were extracted using ammonium acetate and Ca and Mg concentrations were determined by atomic absorption spectrophotometry while K was determined by flame photometry. Soil pH was determined in water using a ratio of 1:5, and soil texture was determined by the hydrometer method. The six experimental sites had SOC ranging from 3.5–8.9 g SOC kg^{-1} soil and clay content ranging from 4–19 %. The soils were mainly acidic with low P and N contents (Table 4.1).

Table 4. 1 Physical and chemical characteristics of soils (0–20 cm) at establishment of experiments in Dendenyore smallholder farming area in Zimbabwe.

Site	Sand (%)	Clay (%)	Organic C (g kg^{-1})	Available P (mg kg^{-1})	Soil pH (H_2O)	Total N (%)	Ca	Mg	K
							(cmol $_{(c)}$ kg^{-1})		
<u>Field type 1 (≤ 4 g C kg^{-1})</u>									
Chingwa	94	4	3.5	3.3	4.4	0.03	0.31	0.18	0.15
Muriva	94	5	4.0	5.5	5.0	0.03	0.44	0.27	0.23
<u>Field type 2 (> 4-6 g C kg^{-1})</u>									
Makoni	94	4	4.6	5.1	4.9	0.05	0.65	0.34	0.42
Chinhengo	80	10	5.4	7.3	4.9	0.04	0.79	0.29	0.43
<u>Field type 3 (> 6 g C kg^{-1})</u>									
Mapiye	84	10	7.3	7.4	5.4	0.05	0.83	0.45	0.52
Muhwati	65	19	8.9	10.5	5.2	0.06	0.98	0.43	0.48

4.2.4 Experimental treatments and management

Field experiments were established on the above described field categories using a nutrient omission trial design, between 25-30 November for both seasons. Land preparation was done using ox-drawn ploughs and plot sizes were 4.5 m x 5m. An early to medium maturity hybrid maize variety SC 513 was planted, at as pacing of 0.9 m x 0.25 m to give a population of 44,000 plants ha^{-1}. Two seeds were planted per station and thinned at two weeks after emergence to one plant per station. Weeding was manually carried out using hand hoes three times during the season. The weeding regime eliminated any crop-weed competition for nutrients and water. The weeding regime was meant to eliminate any crop-weed competition for nutrients and water. The experimental treatments were replicated three times on each field in a randomized complete block design. The experimental treatments were formulated using widely available fertilizer resources as follows:

i. Control (no nutrients added)
ii. NK (muriate of potash (60% K)+ ammonium nitrate(34.5% N)
iii. NPS (single super phosphate(18 P_2O_5 + 9% S)+ammonium nitrate)
iv. PKS (single super phosphate + muriate of potash)
v. NPKS (Compound D (7 N- 14 P_2O_5-7 K_2O +8% S)+ ammonium nitrate + muriate of potash)

The experiment was designed with target nutrient application rates for Year 1 of 40 kg ha^{-1} P, 60 kg ha^{-1} K and 120 kg ha^{-1} N. During Year 2, the target N application rate was maintained while only 20 kg ha^{-1} P and 30 kg ha^{-1} K was applied. Practically, N application was deemed a function of rainfall, with a mandatory initial application of 20 kg ha^{-1} N at planting and two subsequent splits of 50 kg ha^{-1} N, if soil moisture permitted. With this rule, only 70 kg ha^{-1}could be applied for both seasons, due to terminal season droughts that necessitated withholding the second N top dressing application of 50 kg ha^{-1}. High nutrient application rates for P and K were used, compared with prevalent rates commonly used by farmers, to enable determination of attainable yields for the three soil fertility domains when all other variables are maintained the same, including rainfall. All the P, K and S were applied at planting, as compound D (ZFC fertilizers, www.zfc.co.zw), single super phosphate or muriate of potash fertilizer. Due to limitations related to available fertilizers, S could not be isolated and added to the NK treatment.

4.2.5 Determination of maize productivity and nutrient uptake

Yield determination and nutrient uptake were determined according to the methodology elucidated in sections 3.4 -3.4.3.

4.2.6 Determination of indigenous soil nutrient supply capacity

The nutrient omission trial design enables the determination of indigenous N, P and K nutrient supply capacity for different sites. Indigenous nutrient supply (INS) for N, P and K were determined as follows:

- $INS_{Nitrogen}$ = total plant N uptake in a plot where all other nutrients were applied, except N (PKS treatment)
- $INS_{Phosphorus}$ = total plant P uptake in a plot where all other nutrients were applied, except P (NK treatment).
- $INS_{Potassium}$= total plant K uptake in a plot where all other nutrients were applied, except K (NPS treatment)

4.2.7 Predictions for indigenous nutrient supplies using the QUEFTS model

Models that have been successfully validated using field data are important tools as they provide quick alternative ways to deepen the understanding of systems. The Quantitative Evaluation of Fertility of Tropical Soils (QUEFTS) model was developed using data from experiments carried out in Kenya, to estimate indigenous soil N, P and K and crop response to fertilizers (Janssen *et al.,* 1990). The QUEFTS model is a simple tool that allows indigenous nutrient supply and maize yield predictions based on SOC, total N, total P, exchangeable K and pH. The model has been widely used in SSA across agro-ecological zones (Bontkes *et al.,* 2003; Tittonell *et al.,* 2008; Mowo *et al.,* 2006). The QUEFTS model uses the following relations to estimate indigenous nutrient supply by soils:

i. $INS_{Nitrogen}$ =fN x 6.8 x SOC
ii. $INS_{Phosphorus}$ = fP x 0.35 x SOC + 0.5 x extractable P
iii. $INS_{Potassium}$ = fK x 400 x exchangeable K / (2+0.9) x SOC)

[Equations I]

Where SOC is expressed in g C kg^{-1}soil, extractable P in mg P kg^{-1}soil exchangeable K in cmol $_{(+)}$ kg^{-1}soil, and where *f* = correction factors related to pH: fN =0.25 x (pH-3), fP = 1- 0.5 x (pH – 6)^2, and fK = 0.625 x (3.4 – 0.4 x pH). The INS capacity values obtained using these relations were then compared to values obtained from the nutrient omission experiments for the three soil fertility domains.

4.2.8 Determination of maize response to NPK fertilization across sites

Maize yield response was determined as the difference in the attainable yield and the nutrient-limited yield (Xu *et al.,* 2014). For example maize yield response to fertilization of N was determined as the difference in maize yields obtained for the treatment that received all nutrients (NPKS treatment) and the treatment that received all other nutrients, except N,

i.e. response to N (kg ha^{-1}) = grain yield for NPKS – grain yield for PKS. Likewise, response to P (or K) was obtained as the difference in yields between the NPKS and NKS (or NPS) treatments.

This data was further processed to determine N, P and K response factors for the different sites. For example for N, the following relation was used:

$$\text{N response factor} = 1 - \frac{\text{Grain yield without N applied}}{\text{Grain yield with NPKS applied(Yw)}} \text{(Equation II)}$$

This relation provides evidence of degree of limitation of the specified element, in the context of the fertilization strategy for water limited yield potential (Yw), in a way accounting for the 'yield gap' associated with that nutrient for different soil fertility regimes. Agronomic efficiencies for N and P ($AE_{N \text{ or } P}$) were calculated as kg grain produced per kg N or P applied (Equation III; Doberman, 2007). Apparent recovery efficiencies (RE_N or RE_P) were calculated as net N (or P) uptake per quantities nutrients applied (Equation IV).

$$AE_N = \frac{\text{Grain yield with N applied – grain yield when N is omitted}}{\text{Amount of N applied}} \qquad \text{(Equation III)}$$

$$RE_N = \frac{\text{Total N uptake where N was applied} - \text{N uptake where N was omitted}}{\text{Amount of N applied}} \qquad \text{(Equation IV)}$$

4.2.9 Rainfall water productivity estimation

Rainfall water productivity (kg grain mm^{-1} rainfall, RWP) was used as a proxy for water use efficiency for the different nutrient management strategies (Rockstrom *et al.,* 2003). This method oversimplifies rainfall water productivity as it does not account for run-off and evaporation. During both cropping seasons, daily rainfall was recorded using two rain gauges that were situated within 2 km from the 3 experimental sites that were retained for Year 2. Rainfall for these two locations was averaged to get the monthly and seasonal rainfall for the area. The data was then used to compute rainfall water productivity for the different treatments and sites as follows:-

$$\text{Rainfall water productivity} = \frac{\text{Maize grain yield (kg ha}^{-1}\text{)}}{\text{Total in season crop rainfall (mm)}} \quad \text{(Equation V)}$$

4.2.10 Statistical analyses and graphical presentation

Nutrient management and site effects on maize grain and stover yields, and total N, P, and K uptake were examined using analysis of variance (ANOVA) with GENSTAT version 13 statistical package. Site means were separated using Tukey's 95% confidence level. Where appropriate, the least significant differences were used in both tables and figures to separate means. The association between nutrient uptake (N, P, and K) and SOC were explored with simple regressions using Sigma Plot version 10, while box-plots were used to depict the relative responses to N, P or K.

4.3 Results

4.3.1 Rainfall distribution and N management

Monthly rainfall distribution was poor for both seasons, with flooding and drought episodes occurring within the cropping seasons (Figure 4.1). The first season received 780 mm while the second season had 891 mm, both comparable to the average long term rainfall of 825 mm for the area. During Year 1, the month of December received over 400 mm rainfall as compared to February that experienced a severe dry spell for more than 3 weeks. During Year 2, the month of January also received over 400 mm rainfall followed by February that received only 24 mm.

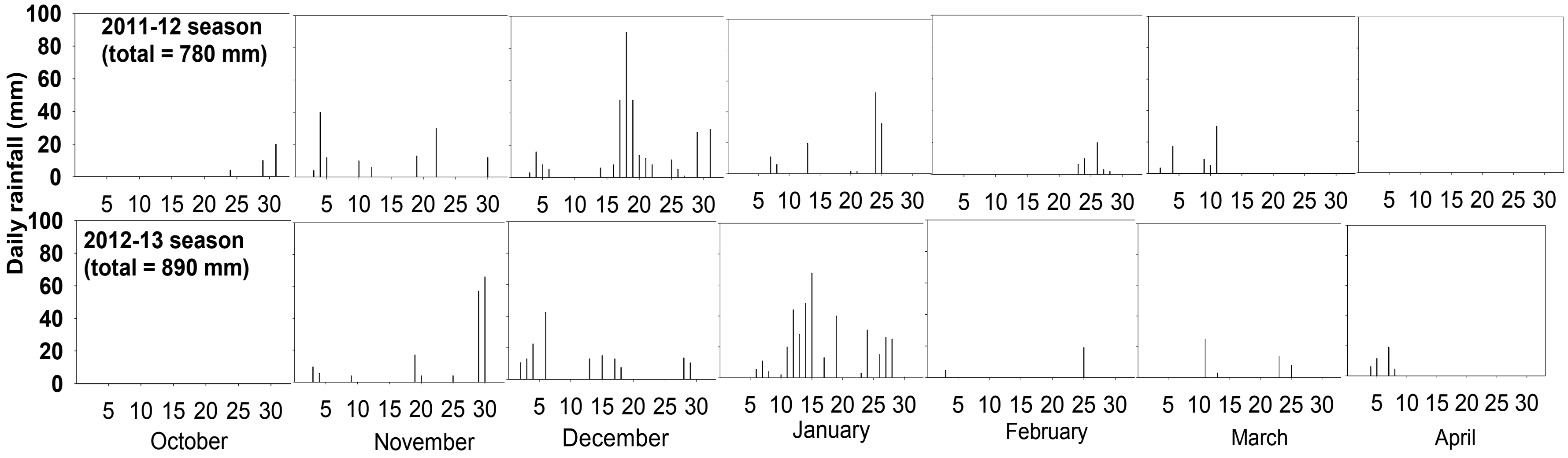

Figure 4.2 Monthly rainfall distribution for 2011/2012 and 2012/2013 cropping seasons, in Dendenyore Ward, Hwedza District, Zimbabwe

4.3.2 Maize productivity and NPK responses

Maize productivity was significantly influenced by nutrient management across all sites, with site mean yields significantly larger for Field Types 2 and 3 when compared to Field Type 1. During the first season, maize yields across sites ranged from 0.25–0.84 t ha^{-1} for the control and 2.05–3.75 t ha^{-1} for the NPKS treatment, with lowest yields on Field Type 1 (Figure 4.2).

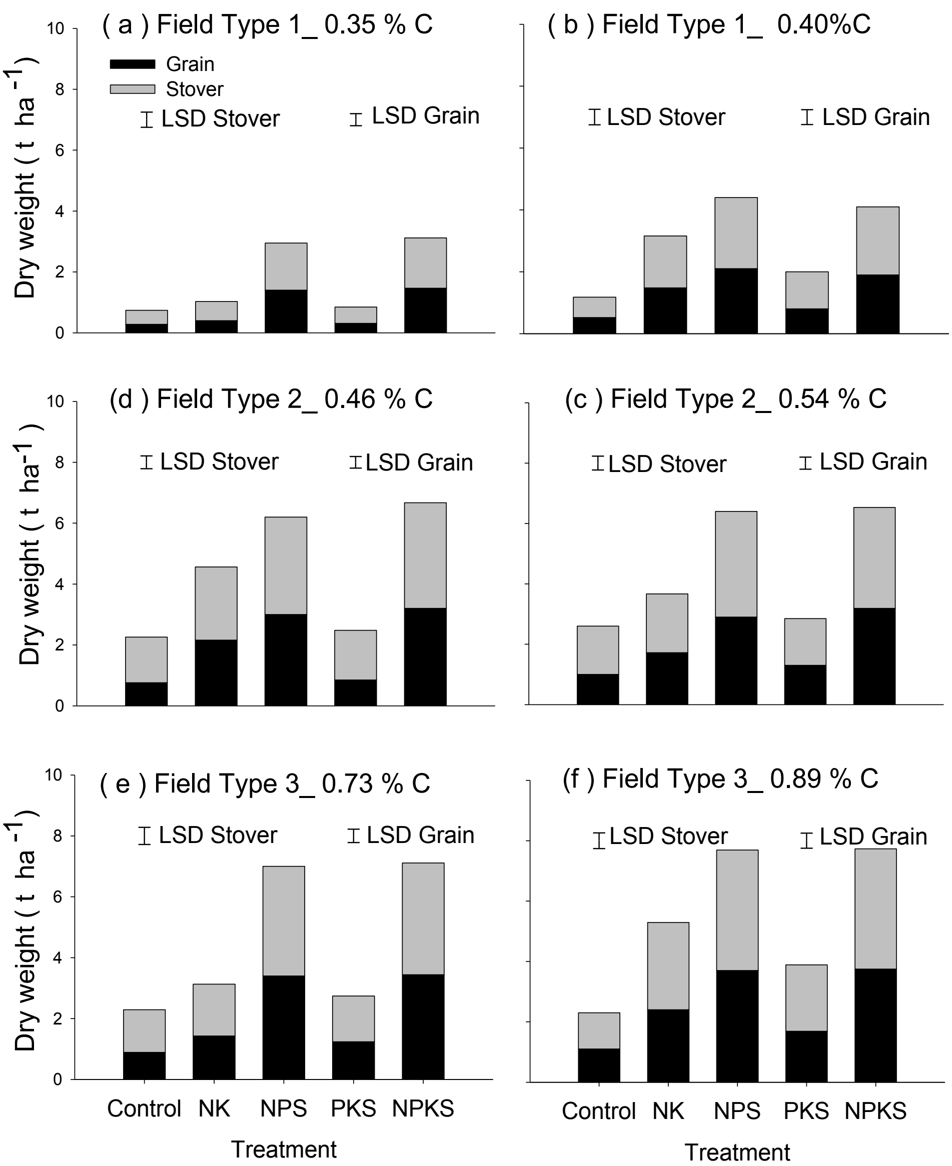

Figure 4. 3 Maize grain and stover yields as influenced by nutrient management across six on-farm sites for the 2011/2012 cropping season (Year 1) in Dendenyore Ward, Hwedza, Zimbabwe

For the second season, that was limited to three sites on a landscape within a one km radius, maize yields for the control ranged from 0.2 – 1.2 t ha^{-1}, while those for the NPKS treatments ranged from 2.42–3.60 t ha^{-1}, with higher yields associated with larger SOC concentration (Figure 4.3). Yields between the PKS treatment and the control were not significantly different within sites and for both seasons. Also notable were the non-significant differences in yields between the NPKS and the NPS treatments, including on the soils with poor SOC content. Yields for the NK treatment were significantly much lower than NPS across all the study sites.

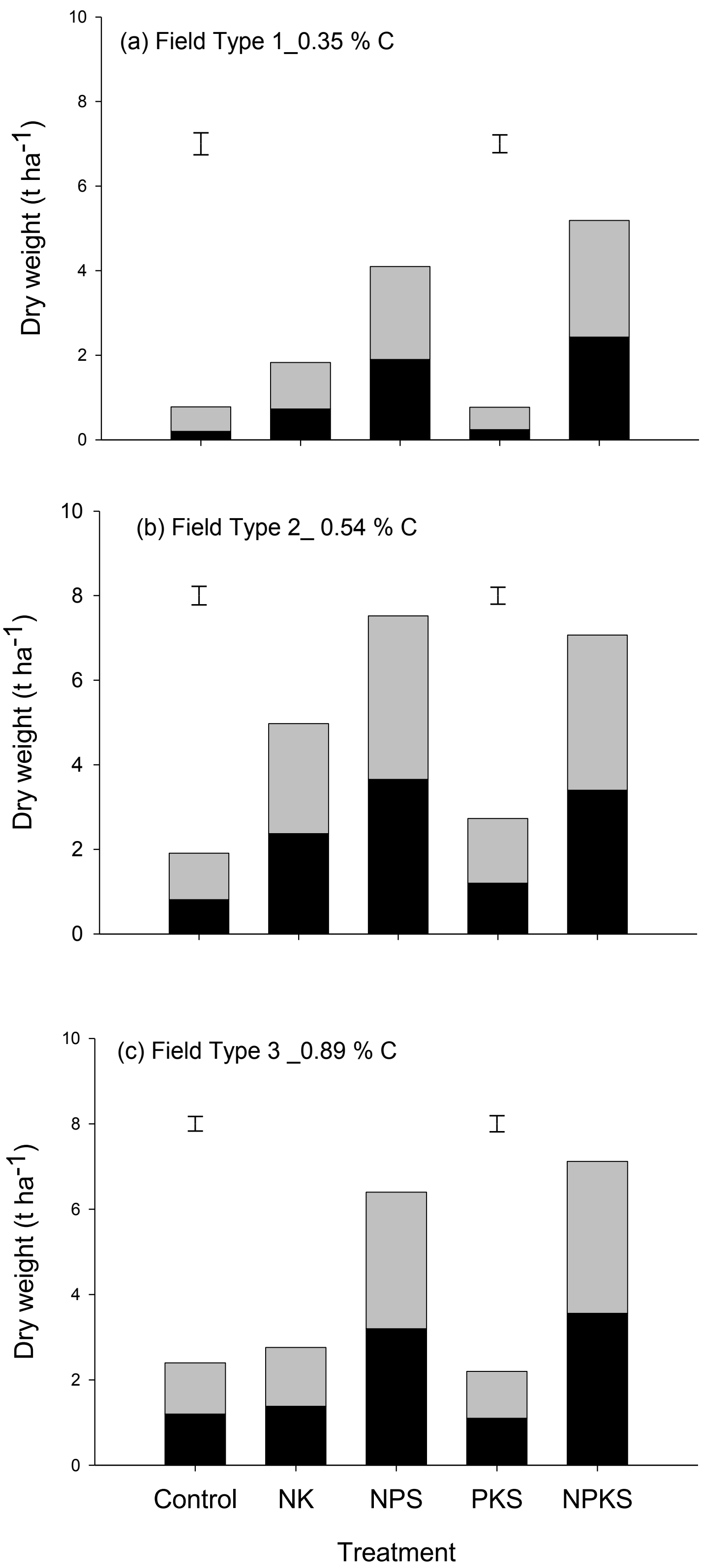
(a) Field Type 1_0.35 % C
(b) Field Type 2_ 0.54 % C
(c) Field Type 3 _0.89 % C
Dry weight (t ha-1)
0
2
4
6
8
10
Control
NK
NPS
PKS
NPKS
Treatment

Figure 4.4 Maize grain and stover yields as influenced by nutrient management across three on-farm sites for the 2012-2013 cropping season (Year 2) in Dendenyore Ward, Hwedza, Zimbabwe

Across sites, response to N ranged from 1.2- 2.35 t ha^{-1}, response to P ranged from 0.71 - 2.10 t ha^{-1} and response to K ranged from 0.08 -0.30 t ha^{-1}, indicating little response to K (Figure 4.4). Maize stover yields followed the same trend.

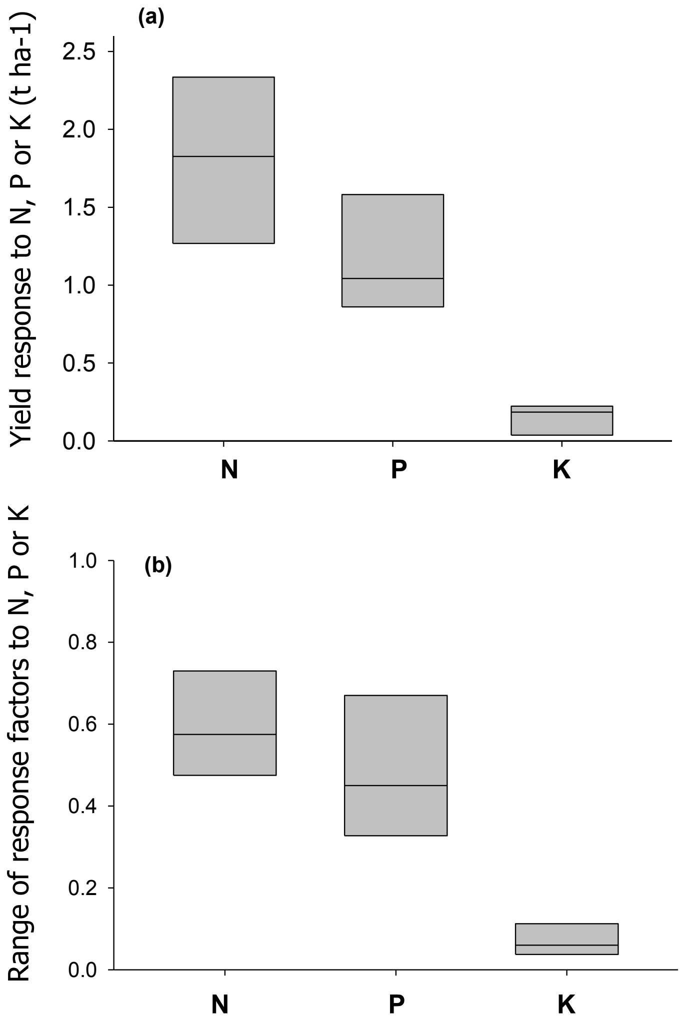

Figure 4.5 Nitrogen, P and K yield responses (a) and N, P and K response factors (b) across six sites during the 2011/12 cropping season (Year 1) in Dendenyore Ward, Hwedza, Zimbabwe.

*The solid horizontal lines within the box-plots represents the mean values.

Using the NPKS mean yields for the different sites as proxies for water limited 'attainable' yields for the two years, the corresponding N, P and K response factors, as computed using Equation II, ranged from 0.47-0.72 for N, 0.32-0.67 for P and 0.03-0.12 for K, with average values of 0.56, 0.45 and 0.09, indicating a poor response to K and highest response to N application (Figure 4.4 b).

4.3.3 Nutrient uptake by maize

Total N, P and K uptake were determined through analyses of both grain and stover at harvest. Generally the internal concentration of N for grain was conserved, and ranged between 1.45–1.65% while N content in stover ranged between 0.55 – 0.78%. Phosphorus concentration in grain ranged from 0.23–0.29% across sites and treatments, while stover P content averaged 0.18% with little variation. Potassium concentration in maize grain averaged 0.33% and 1.5% in stover. When this data was linked to the corresponding grain and stover productivity, the results indicated that nutrient uptake was significantly influenced by soil quality, with the control treatment for Field Type 1 having the lowest total N, P and K uptake of 7.2, 1.6 and 7.8 kg ha^{-1}, respectively, compared to the control treatment for Field Type 3 that had total N, P and K uptake of 24.8, 5.2 and 21.6 kg ha^{-1}, respectively (Tables 4.2 and 4.3).

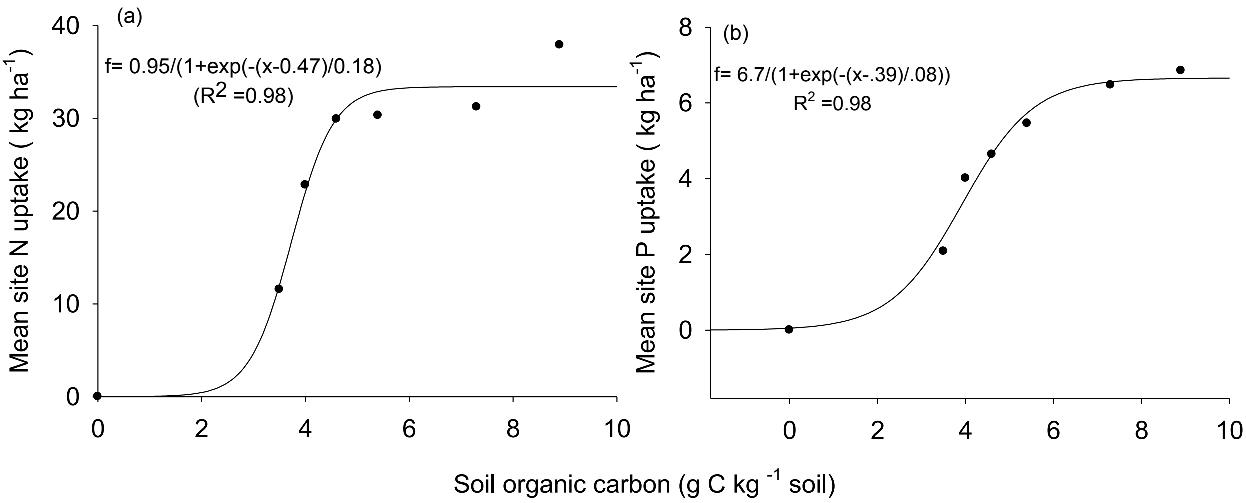

Figure 4.6 Mean site grain N uptake (a) and mean site grain P uptake (b) as a function of SOC concentration

When site N and P grain uptake averages were plotted against SOC, there was strong evidence of SOC having a large impact on nutrient uptake (Figure 4.5). The NPKS treatment also showed a similar trend, with total N, P and K uptake for Field Type 1 of 33.4, 7.1 and 29.6 kg ha^{-1}, respectively, compared to 83.8, 17.6 and 72.1 kg ha^{-1}for Field Type 3.

Table 4. 2 Total above ground N, P and K uptake (kg ha^{-1}) as influenced by different nutrient application strategies and soil fertility domains during the second season, Hwedza, Zimbabwe

Soil fertility domain	Treatment	Total N uptake	Total P uptake	Total K uptake
			kg ha^{-1}	
	Control	7.22^{a}	1.6^{a}	7.8^{a}
Field Type 1	NK	10.2^{a}	2.7^{b}	10.8^{a}
[Chingwa, C=3.5 g C kg^{-1}]	NPS	31.7^{b}	6.7^{c}	27.9^{b}
	PKS	8.2^{a}	1.8^{a}	9.1^{a}
	NPKS	33.4^{b}	7.1^{c}	29.6^{b}
	LSD	*11.2*	*2.0*	*14.5*
	Control	12.3^{a}	2.6^{a}	11.6^{a}
Field Type 1	NK	33.8^{b}	7.2^{b}	30.1^{bc}
[Muriva, C =4 g C kg^{-1}]	NPS	47.4^{bc}	10.0^{b}	41.4^{c}
	PKS	14.4^{a}	3.12^{a}	14.0^{ab}
	NPKS	53.2^{c}	11.2^{b}	45.4^{c}
	LSD	*16.6*	*3.0*	*19.3*
	Control	21.2^{a}	4.8^{a}	25.0^{a}
Field Type 2	NK	48.9^{b}	10.4^{b}	43.1^{bc}
[Makoni, C= 4.6_g C kg^{-1}]	NPS	67.2^{bc}	14.2^{b}	57.9^{cd}
	PKS	23.4^{a}	5.3^{a}	27.3^{ab}
	NPKS	72.0^{c}	15.2^{b}	62.6^{d}
	LSD	*24.7*	*4.0*	*18.7*
	Control	25.6^{a}	5.68^{a}	27.3^{a}
Field Type 2	NK	39.2^{a}	8.3^{a}	34.9^{a}
[Chinengo, =5.4 g C kg^{-1}]	NPS	67.4^{b}	14.4^{b}	62.1^{b}
	PKS	30.1^{a}	6.4^{a}	27.5^{a}
	NPKS	71.1^{b}	14.9^{b}	60.6^{b}
	LSD	*20.6*	*3.7*	*16.3*
	Control	22.6^{a}	5.0^{a}	23.9^{a}
Field Type 3	NK	33.1^{a}	7.1^{a}	30.2^{a}
[Mapiye, =7.3 g C kg^{-1}]	NPS	76.0^{b}	16.0^{b}	65.2^{b}
	PKS	28.8^{a}	6.2^{a}	26.6^{a}
	NPKS	77.1^{b}	16.2^{b}	66.1^{b}
	LSD	*15.2*	*2.7*	*14.3*
	Control	24.8^{a}	5.2^{a}	21.6^{a}
Field Type 3	NK	55.7^{b}	11.9^{b}	51.3^{c}
[Muhwati, =8.9 g C kg^{-1}]	NPS	83.1^{c}	17.5^{c}	72.1^{d}
	PKS	23.3^{a}	9.8^{b}	33.1^{b}
	NPKS	83.8^{c}	17.6^{c}	72.1^{d}
	LSD	*13.8*	*2.5*	*10.2*

Means followed by same letters within the column did not differ significantly at $P < 0.05$.

Table 4. 3 Total above ground N, P and K uptake (kg ha^{-1}) as influenced by different nutrient application strategies and soil fertility domains during the second season, Hwedza, Zimbabwe.

Soil fertility domain	Treatment	Total N uptake	Total P uptake	Total K uptake
			kg ha^{-1}	
	Control	4.8^{a}	1.0^{a}	9.1^{a}
Field Type 1	NK	13.1^{a}	2.75^{b}	12.3^{a}
[Chingwa, C=3.5 g C kg^{-1}]	NPS	26.7^{b}	6.22^{c}	30.4^{b}
	PKS	5.5^{a}	1.14^{a}	5.2^{a}
	NPKS	26.7^{b}	5.58^{c}	30.3^{b}
	LSD	*9.7*	*1.7*	*14.5*
	Control	23.75^{a}	3.8^{a}	12.3^{a}
Field Type 2	NK	53.2^{b}	11.1^{b}	28.5^{ab}
[Chinengo, C =5.4 g C kg^{-1}]	NPS	47.4^{b}	15.1^{b}	40.0^{b}
	PKS	26.5^{a}	5.5^{a}	12.0^{a}
	NPKS	73.7^{c}	15.4^{b}	42.4^{b}
	LSD	*12.6*	*3.8*	*19.3*
	Control	24.2^{a}	5.1^{a}	25.0^{a}
Field Type 3	NK	46.4^{b}	9.7^{b}	43.1^{ab}
[Muhwati, C= 8.9 g C kg^{-1}]	NPS	71.9^{c}	14.2^{c}	57.9^{b}
	PKS	25.8^{a}	5.4^{a}	27.3^{a}
	NPKS	76.5^{c}	16.0^{c}	62.6^{b}
	LSD	*20.3*	*3.6*	*22.1*

Means followed by same letters within the column did not differ significantly at $P < 0.05$
Field Type 1 — ≤ 4 g C kg^{-1} soil, Field Type 2 — >4 -6 g C kg^{-1} soil, Field Type 3— >6 g C kg^{-1} soil

4.3.4 Nitrogen, P and K use efficiencies across soil fertility domains

The agronomic efficiency of phosphorous (AE_P) for the NPS and NPKS treatments were also comparable for Field Types 2 and 3, ranging between 28–67 kg grain kg^{-1} P for the NPS and NPKS treatments compared to a paltry 0.5–14 kg grain kg^{-1} P applied for the PKS treatment. Application of K had a small impact on yield across all the field types with the largest $AE_K < 1$ kg grain kg^{-1} K applied (data not shown). Recovery efficiencies (RE) followed the same trend, with a low RE_N for Field Type 1 compared to Field Types 2 and 3 (Tables 4.4 and 4.5). In many cases, RE_N at least doubled when P was co-applied.

Table 4. 4 Nitrogen and P agronomic efficiencies [A] and N and P recovery efficiencies [B] for the first cropping season as influenced by nutrient management and soil resource base in Dendenyore, Hwedza, Zimbabwe

[A]

Site	(g C kg^{-1} soil)	NK	AE_N NPS	NPKS	AE_P NPS	PKS	NPKS
		kg grain kg^{-1} N applied			kg grain kg^{-1} P applied		
Chingwa	3.5	1.7	16.0	17.0	28.0	0.5	29.3
Muriva	4.0	13.7	22.5	26.7	39.5	2.3	41.2
Makoni	4.6	10.3	27.0	31.2	47.5	7.5	50.4
Chinhengo	5.4	20.0	32.0	34.8	56.0	2.2	56.3
Mapiye	7.3	17.7	35.8	36.4	62.7	8.7	64.1
Muhwati	8.9	18.5	37.1	37.8	65.0	14.	67.0

[B]

Site	(g C kg^{-1} soil)	NK	RE_N NPS	NPKS	RE_P NPS	PKS	NPKS
		Fraction N uptake (kg kg^{-1})			Fraction P uptake (kg kg^{-1})		
Chingwa	3.5	0.04	0.31	0.37	0.17	0.18	0.20
Muriva	4.0	0.32	0.47	0.60	0.25	0.10	0.27
Makoni	4.6	0.19	0.61	0.66	0.33	0.02	0.32
Chinhengo	5.4	0.40	0.67	0.73	0.32	0.01	0.33
Mapiye	7.3	0.14	0.75	0.77	0.26	0.03	0.27
Muhwati	8.9	0.44	0.83	0.84	0.30	0.08	0.31

In one case, the REP was as little as 1% for the PKS treatment, increasing to a remarkable 30% when both N and P were applied. Nitrogen, P and K agronomic use efficiencies were mainly influenced by treatment and SOC levels (Tables 4.4 and 4.5). Fertilization with NPKS and NPS produced the highest AE_N across sites, ranging from 16–37.8 kg grain kg^{-1} N, whereas the NK treatment had an AE_N range of 1.7–20 kg grain kg^{-1} N applied across all sites. Agronomic efficiencies were always lowest for the Field Type 1 domain as compared with Field Types 2 and 3 that were not significantly different.

Table 4. 5 Nitrogen and P agronomic efficiencies [A] and N and P recovery efficiencies [B] for the second cropping season as influenced by nutrient management and soil resource base in Hwedza, Zimbabwe

4.3.5 Experimentally and QUEFTS-derived indigenous nutrient supply (INS) capacity

[A]							
Site	(g C kg^{-1} soil)	NK	AE_N NPS	NPKS	NPS	AE_P PKS	NPKS
		kg grain kg^{-1} N applied			kg grain kg^{-1} P applied		
Chingwa	3.5	7	16.0	17.0	31.5	2	35.5
Chinhengo	5.4	12.1	35.2	31.4	51.8	13.3	51.4
Muhwati	8.9	14.1	29.9	36.3	50.5	14.1	52.4
[B]							
Site	(g C kg^{-1} soil)	NK	RE_N NPS	NPKS	NPS	RE_P PKS	NPKS
		Fraction N uptake (kg kg^{-1})			Fraction P uptake (kg kg^{-1})		
Chingwa	3.5	0.03	0.31	0.35	0.10	0.11	0.12
Chinhengo	5.4	0.40	0.71	0.72	0.15	0.0	0.16
Muhwati	8.9	0.44	0.79	0.83	0.15	0.02	0.15

The capacity of the soil to supply N, P or K ($INS_{Nitrogen}$, $INS_{Phosphorus}$, $INS_{Potassium}$) was experimentally derived using nutrient uptake data from plots that had optimally received all other nutrients except the nutrient under investigation. The $INS_{Nitrogen}$ ranged from as little as 8.5 kg ha^{-1} for Field Type 1 to 27.6 kg ha^{-1} at one of the Field Type 3 sites (Table 4.2). The corresponding $INS_{Phosphorus}$ ranged from 2.2 kg ha^{-1} for Field Type 1 to 11.7 kg ha^{-1} for Field Type 3. Generally, these results suggest that these soils had little capacity to supply indigenous N and P at yield levels above 2 t ha^{-1}, including Field Type 3 sites. In contrast, the $INS_{Potassium}$ capacity was relatively high, ranging from 26–70 kg ha^{-1}. Relations from QUEFTS were used to estimate the capacity of these soils to supply N, P and K. Computations with QUEFTS indicated that the indigenous N, P and K supply capacity ranged from 10–37 kg ha^{-1}, 6.1–8.2 kg ha^{-1}, and 25–62 kg ha^{-1}, respectively (Table 4.2).

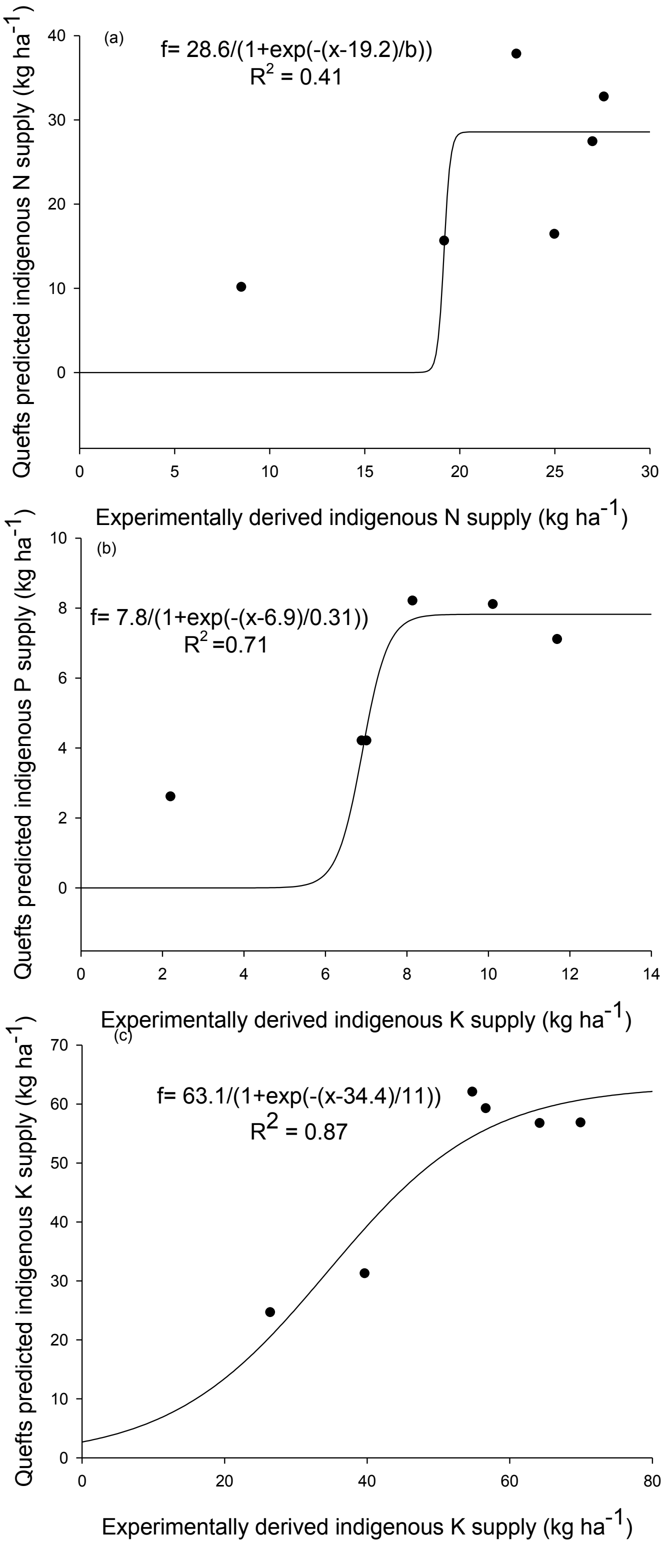

Figure 4.7 The relationship between the experimentally-derived and QUEFTS predicted indigenous nutrient supply capacity for (a) N, (b) P and (c) K across six on-farm sites, Hwedza, Zimbabwe

4.3.6 Water productivity

Rainfall water productivity (kg grain mm^{-1} rainfall) was a function of both soil fertility status and nutrient application strategies (Figure 4.7).

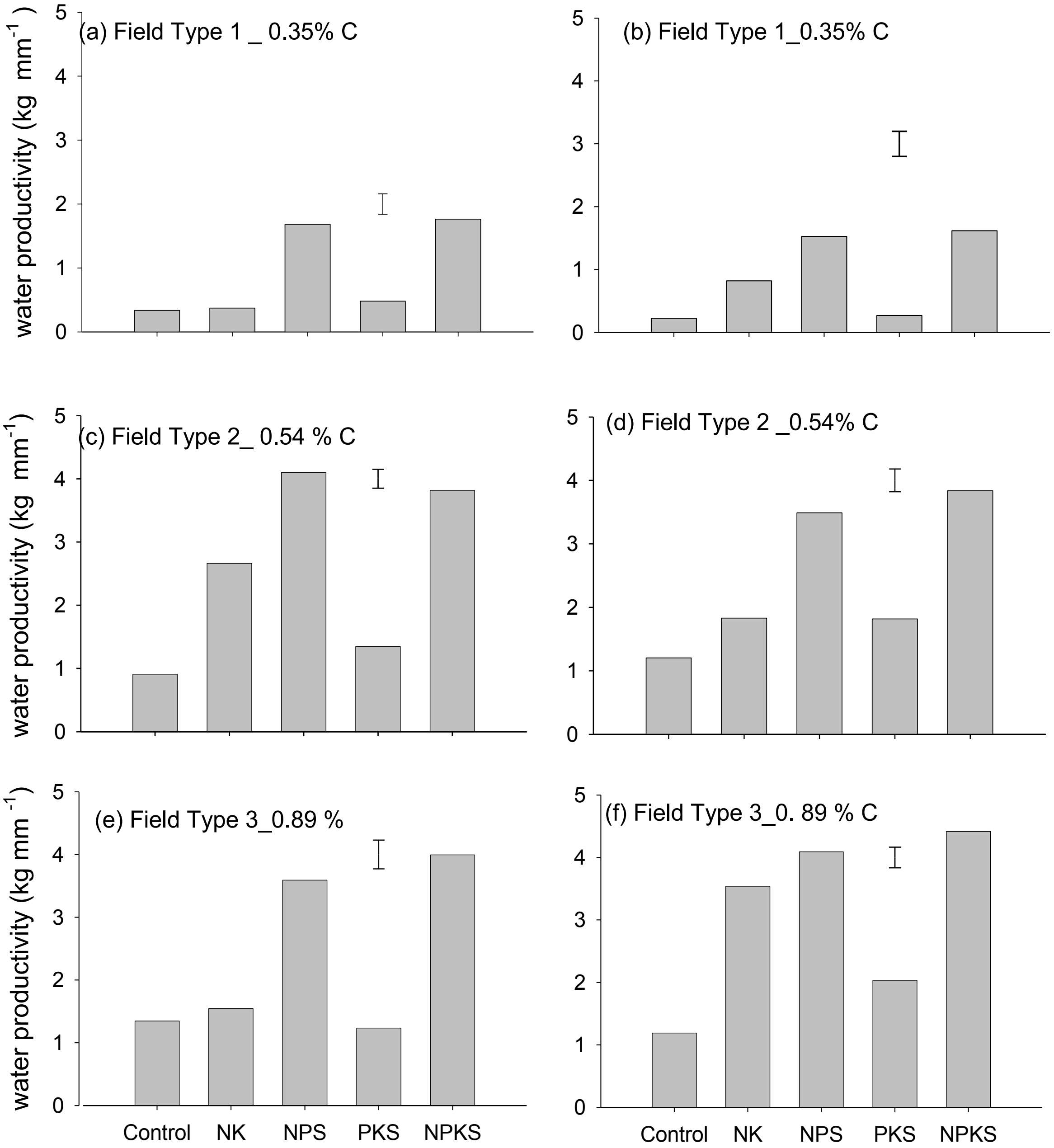

Figure 4.8 Water productivity (kg grain mm-1 rainfall) as influenced by nutrient management across three experimental sites belonging to different soil fertility domains during two cropping seasons, Hwedza, Zimbabwe

Using maize productivity data for the second cropping season that received 890 mm rainfall, rainfall water productivity for Field Type 1 ranged from as little as 0.25 kg grain mm^{-1} for the control to a maximum of only 1.62 kg grain mm^{-1} for the NPKS treatment. The corresponding range for rainfall water productivity for Field Type 2 was 0.91–4.1 kg grain mm^{-1} while Field Type 3, the range was 1.34–4.00 kg grain mm^{-1} rainfall (Figure 4.7).

4.4 Discussion

4.4.1 Maize grain yields response to nutrient application

Maize productivity was lowest in the Field Type 1 category (<4 g SOC kg^{-1} soil), with yields as low as 0.2 t ha^{-1} without added nutrients and maximum yields not exceeding 2.5 t ha^{-1} for the NPKS treatment (Figures 4.2 and 4.3). Maize grain yields were significantly larger for Field Types 2 and 3 compared to Field Type 1. Consistently, there were no differences between the NPS and NPKS treatments across the three soil fertility domains, suggesting that the indigenous soil K supply was adequate to support maize production at yield levels < 5 t ha^{-1}. Generally, Zimbabwean dolerite and granite-derived sandy soils are rich in feldspar minerals that act as K reserves (Nyamapfene, 1991). However, it is anticipated that under well distributed rainfall conditions, and when productivity can be raised to >8 t ha^{-1} through a combination of liming, and organic-inorganic nutrient combinations, the K demand by maize will exceed the rate of K release from soil minerals, and response to externally applied K will manifest. Currently, K is a mandatory composition of compound fertilizers that are marketed in Zimbabwe, in what is described as K maintenance dressing.

Yields for both NK and PKS treatments were poor across sites (Figures 4.2 and 4.3), confirming that co-application of N and P is critical for optimum crop growth in the cropping system. In many cases, there were no differences in yields between the control and the PKS treatment, despite relatively high application rates of 40 kg ha^{-1} P and 60 kg ha^{-1} K during Year 1. A yield response was only realized when N was added. These results represent a classic example of the law of the most limiting nutrient and crop growth, and the indispensable need for balanced nutrient application. This is in line with results from West Africa, where significant improvements in RE_N were observed on simultaneous application of N and P (Fofana *et al.,* 2005). Often, smallholder farmers have managed to sustain low maize production levels by managing soil fertility through application of a combination of small quantities of livestock manure, compost and spreading nutrient-rich termitaria soils around the crop fields (e.g. Mtambanengwe and Mapfumo, 2006). Though concentration of nutrients in these resources is low, the little macro- and micronutrients that become available avert acute nutrient deficiencies, making production of base yields possible.

4.4.2 The responsive-non responsive soils discourse

Acutely degraded fields have been reported to respond poorly to nutrient additions in terms of crop yields, which has been termed the 'non-responsive soil' phenomena (Kho, 2000; Tittonell *et al.,* 2005; Zingore *et al.,* 2007). Despite the very low SOC concentration for Field Type 1 in this study (< 4 g kg^{-1} soil), maize yields were increased from a paltry 0.28 t ha^{-1} when no nutrients were applied to 1.46 t ha^{-1} with NPKS fertilizer. In contrast, truly no-responsive soils barely have this response magnitude due to complex biophysical problems that encompass acute nutrient deficiencies, soil acidity, aluminium toxicity and severe P fixation. The yield gains were however marginal, giving sub-optimal agronomic efficiencies (Tables 4.4 and 4.5). Long-term lack of adequate mineral and organic nutrient resources has led to the expansion of fields under Field Type 1, as farmers allocate limited nutrient resources to specific fields, maintaining higher productivity capacity. The neglected fields are then cropped without any external nutrient inputs, gradually becoming exhausted of nutrients and concomitantly becoming acidic as well. At this stage, application of NPK fertilizers often results in poor nutrient use efficiencies. Resuscitating these fields to profitable crop production becomes a challenge, calling for interventions that must include combinations of organic and mineral fertilizers sources. Giller *et al.* (2006) suggested that other nutrients critical to maize growth would need to be applied to enable greater responsiveness to N and P. There was no evidence that K is in this category of nutrients that ameliorate these fields that sub-optimally respond to fertilizers. These soils are best rehabilitated through additions of livestock manure, although this is not always feasible given limited livestock ownership among smallholder farmers (Zingore *et al.,* 2007).

In this study Field Types 2 and 3 had comparable yields and nutrient use efficiencies (Figure 4.2; Tables 4.2, 4.3). This affirms the existence of critical SOC threshold at about 4.6 g kg^{-1} soil, beyond which a steep increase in nutrient use efficiencies sets in (Mtambanengwe and Mapfumo, 2005). This offers opportunities for guidelines that allow farmers to use scarce organic resources efficiently by applying them to a wider area to achieve this SOC threshold, as opposed to concentrating organic inputs on already fertile fields with little benefits accruing from the resultant additional SOC beyond threshold content.

4.4.3 QUEFTS and nutrient supply capacity predictions

Experimentally derived indigenous N, P and K supply were compared with QUEFTS derived values (Figure 4.6 a,b,c). Phosphorus and K supply potential were well predicted by QUEFTS with r^2 values of 0.71 and 0.87, respectively, while N prediction was poor (r^2 of 0.41). These results suggest that there is potential for quick explorations using QUEFTS if soil pH, SOC and extractable P and K are known, to estimate P and K supply potential by sandy soils. This information is vital in deciding the level of fertilization to use based on yield targets, aiding informed targeting of scarce nutrient resources. The lack of good agreement between QUEFTS-predicted and experimentally derived N is of concern as N is one of the most important nutrients in maize production on the vast sandy soils in Zimbabwe. The reason for this could be the incomplete uptake of N in the nutrient omission plots resulting in poor correlation as N is highly mobile and resulted in very low values for the nutrient omission plots (Tittonell *et al.,* 2008).

4.4.4 What is the SOC threshold for economic fertilizer use under variable rainfall?

Results from the study are consistent with sandy soils that have SOC <4 g kg^{-1} soil that are associated with low nutrient use efficiencies. Response to fertilizer application was observed to be adequate at a site with SOC as low as 4.6 g kg^{-1} soil, comparable to a site that had 0.89% SOC. This study was not of a scope that allowed determination of a SOC cut-off point for responsiveness to fertilizers, but rather indicated that there is scope for farmers with Field Types 2 and 3 to produce maize at > 3.5 t ha^{-1} through appropriate fertilizer inputs. Elsewhere, studies for minimum SOC thresholds have not been conclusive. For instance, Bationo *et al.* (1998) found a strong mineral fertilizer response in soils with SOC as low as 0.17 %, while in northern Guinea, Berger *et al.* (1987) established a SOC threshold of 3.5 g kg^{-1} soil. In this study, sites that had SOC that was at least 4.6g kg^{-1} soil (Field Types 2 and 3) had higher yields for the control plots, indicating a sizeable indigenous nutrient supply capacity. This study was limited to a few representative fields that were strategically chosen to be within a short distance apart, as a way to reduce confounding effects due to rainfall differences across sites, a common impediment in interpreting nutrient responses from multi-locational experiments. As a trade-off to multi-locational sites for a study of this nature, it was perceived that controlling for rainfall would provide a better platform towards unravelling the SOC - nutrient use efficiencies nexus. Thus, the approach partially contributes to the site-specific fertilizer recommendations discourse.

Occurrence of dry spells and flooding conditions during the growing period is one of the factors that confound response to fertilizer application. Nitrogen applied as top-dressing is prone to leaching in light-textured soils, and also is poorly utilized when drought conditions coincide with the peak N demand period. A flexible system of fertilization that vary top-dressing N fertilizer according to the current seasonal rainfall pattern, that was used in this study, offers opportunities for farmers to reduce large losses of fertilizer investment when the rainfall fails (Piha, 1993). While total monthly or seasonal rainfall is indicative of the potential for sustaining certain yield levels, it is ultimately its distribution that will count more at local level. As Mortimore and Adams (2001) suggest, the challenges faced by farmers are related to the need for enhanced ability to '*negotiate the rains*' each year. And that is difficult when appropriate weather forecasting information from the local meteorological services hardly reaches the farmers, or if it does, it is received with skepticism due to past experiences in which some of the relayed meteorological messages were inaccurate.

4.5 Conclusions

The study has revealed that response to nutrient application is strongly linked to the initial soil fertility condition, with SOC <4g kg^{-1} soil associated with poor nutrient use efficiencies. The differences in yield response to NPKS for soils with SOC ranging from 4.6-9.0 g kg^{-1} (Field Type 2 and 3) soil were not significant, suggesting the possibility for a critical SOC threshold associated with good response to added nutrients, being achieved within this range. This work also confirmed N and P as the overriding limiting nutrients, and that while K is part of most marketed compound fertilizers in Zimbabwe, prevailing maize productivity on these soils can be readily supported by soil-derived K. Further, addition of K did not enhance soil responsiveness to N or P. This however, does not mean K must not be included in the fertilizer as it must be added to prevent nutrient mining in the long term and partly to support yields in excess of 5 t ha^{-1}. Current blanket fertilizer recommendations fall short of addressing the spatial heterogeneity in farms, leading to poor nutrient use efficiencies. Balanced nutrient management had an overriding effect on maize grain and water productivity, but was only guaranteed when soil SOC >4 g kg^{-1} soil. Other than fertilization strategies with N and P-based mineral sources, complementary organic nutrient management approaches should be employed to increase soil SOC and sustain soil productivity. In this study, Field Types 2 and 3 had comparable yields and nutrient use efficiencies. This is rather intriguing, but the existence of a critical SOC threshold at about 4.6 g C kg^{-1}, beyond which a steep increase in nutrient use efficiencies sets in could be the case. Efficient management of limited amounts of organic resources in smallholder farming systems will largely depend on targeting application rates to maintain SOC levels that support good response to fertilizer as opposed to concentrating the organic inputs on already fertile fields with little benefits accruing from the additional SOC beyond threshold contents.

CHAPTER 5

SHORT-TERM EFFECTS OF MINERAL FERTILIZERS, MANURE AND LIME ON MAIZE PRODUCTIVITY ACROSS SOIL FERTILITY DOMAINS ON SMALLHOLDER FARMS IN ZIMBABWE

Abstract

Maize (*Zea mays* L.) is the staple food in Zimbabwe, but low soil fertility and lack of effective fertilization strategies for variable soil conditions hamper efficient use of nutrient resources. The overall objective of this study was to establish the influence of soil fertility heterogeneity on maize productivity, and yield response to manure, liming and inorganic fertilizers. Three sites, selected to represent three soil fertility domains based on soil organic carbon (SOC) between 3.5–8.9 g C kg^{-1} soil, were used during two cropping seasons. Nitrogen, P, K and S were applied alone (NPKS) or in combinations involving lime, cattle manure and micronutrients in a complete randomised block design experiment with three replicates. Plot sizes were 4.5 m x 5 m. Data was analysed by a general analysis of variance (ANOVA) with site, treatment and year as factors. There was a significant site x treatment interaction ($P < 0.01$). Across sites, maize grain yields increased with increasing SOC. Yields for the control ranged from 0.37 to 1.05 t ha^{-1}, differing significantly from the yields for the NPKS treatment that ranged from 2.14 to 4.60 t ha^{-1}. The NPKS plus manure ranged from 2.67 to 5.55 t ha^{-1} and were significantly higher than for the NPKS treatments. Manure alone increased yields significantly P (<0.01) on the medium and best fertility field types but only to a maximum of 2.05 t ha^{-1} at one site. Maize yields and nutrient uptake were strongly affected by SOC content, with yields for a site with 3.5 g SOC kg^{-1} soil significantly lower than the two sites that had > 4 g SOC kg^{-1} soil. Farmers must strategically target their limited nutrients resources to fields that are not yet degraded by adding manure and NPKS fertilizer to maintain soil fertility to guarantee returns to fertilizer investments.

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5.1 Introduction

Maize (*Zea mays* L.) is the staple food in much of Southern Africa. However, sustainable maize production intensification is hampered by poor soil fertility and lack of site-specific fertilization strategies. Site specific recommendations are not simple to come up with as they are time consuming and also difficult to come up with for the various soils (Biermacher, 2006). The practicability of the fertilizer manufacturers to come up with different formulations for the different fertility levels is impossible as manufacturers cannot manufacture such a wide range of products and make profits. This is further challenged by highly variable indigenous soil nutrient supplying capacity and inconsistent rainfall patterns. Sandy soils, derived from granitic parent material, constitute 74% of smallholder farming areas of Zimbabwe (Grant, 1981; Nyamapfene, 1989). These soils have inherently poor nutrient supply capacity due to poor soil organic matter. They are generally acidic with low levels of calcium (Ca) and magnesium (Mg) (Grant, 1981).

Smallholder farmers require more innovative approaches in targeting their meagre nutrient resources to fields that offer the best returns, while also actively pursuing practices that regenerate or protect the available soil resource base. This calls for appropriately tailoring soil nutrient management strategies in environments that are well documented as highly heterogeneous in soil fertility conditions (Giller *et al.,* 2011; Tittonell *et al.,* 2006; Zingore *et al.,* 2007). Balanced fertilization in marginal soils has been well established as the key to enhanced nutrient use efficiencies (Janssen, 1998; Kho, 2000; Chikowo *et al.,* 2010, Vanlauwe *et al.,* 2006), yet, often only macronutrient application is prioritized, even in systems where little or no organic inputs are used. In most cases fields that are very low in soil organic matter (SOM) will give poor returns to fertilizers that supply N, P and K only, given the wide range of secondary and micronutrients also deficient in these situations. Often, these are soils with a long history of maize mono-cropping, along with detrimental practices such as burning of crop residues as part of traditional land preparation strategies. Technologies that only address macronutrient deficiencies fail as additional secondary and micronutrient-induced imbalances deter crop growth.

Challenges related to multiple soil nutrient deficiencies, including micronutrients such as zinc (Zn) and boron (B), on light textured soils in smallholder farming systems in Zimbabwe have been reported in isolated studies (Mashiringwani, 1983; Nyamapfene, 1991; Tagwira *et al.,* 1993; Manzeke *et al.,* 2012). The majority of soil fertility research on these soils has focused on the macronutrients NPK, (e.g. Mugwira and Murwira, 1997; Dhliwayo *et al.,* 1998; Mtambanengwe and Mapfumo, 2009), with little empirical evidence on nutrient responses across fertility gradients when several parameters are controlled. The heterogeneous biophysical and socio-economic realities on the ground tend to suggest a need for more finely tailored fertilization strategies that are responsive to these variables (Snapp *et al.,* 2003; Mtambanengwe and Mapfumo, 2009). Regrettably, such tailor-made or precision nutrient management recommendations are fraught with practical impediments, including questions related to the scale at which recommendations have to be made, in farming systems that have steep soil fertility gradients within short distances.

In addition to integrating leguminous crops for enhanced N cycling and using locally available organic nutrient resources, there is consensus that both fertilizer use and nutrient use efficiencies have to substantially increase to guarantee food security. Attempts to systematically assess the agronomic impacts of nutrient management strategies that also involve use of livestock manure or liming, while taking into account heterogeneity in soil resource base are scarce. The multiple and complex chemical and biophysical constraints to crop productivity in depleted soils necessitate an integrated soil fertility management approach that not only address nutrient deficiencies but also soil acidity and poor soil structure associated with low SOC contents. Soil organic carbon is known to be one of the robust indicators of soil health (Bationo *et al.,* 2006), and can be used as an indicator to predict soil productivity potential and yield responses to fertilizer, manure and liming.

The value of defining SOM thresholds has been debated, but there is increasing evidence that it is a key regulating factor for crop performance on African smallholder farms. These are often soils with a long history of cereal mono-cropping with detrimental practices such as burning of crop resl8idues as part of traditional land preparation. In a chronosequence in Kenya, fields were identified that varied in duration of fallow period, where a strong 'S-shaped'relationship was observed between maize fertilizer response and SOM pools (Marenya and Barrett, 2009). Poor crop yield response to NPK fertilizer application under low SOM conditions is often associated with poor soil physical properties, chemical imbalances and deficiencies of micronutrients.

To investigate the response of soils and maize productivity to secondary and micronutrients across fertility gradients, an experiment was established at three field sites in a smallholder farming community in Zimbabwe with the following specific objectives: (1) to assess productivity of maize following sole or co-application of manure, lime, micronutrients and NPK-based fertilisers, (2) to evaluate the interactive effects of macro and micronutrients, manure and liming on soils differing in organic carbon levels, and (3) to determine water productivity under different fertilization strategies in relation to soil organic carbon and/or soil texture under similar rain-fed conditions.

5.2 Materials and methods

5.2.1 The study area description

The study was conducted on smallholder farms in Dendenyore ward (18°15' latitude, 32°22' longitude), Hwedza district, in Eastern Zimbabwe, during the 2011/12 and 2012/13 cropping seasons. Soil fertility variability within and among farms is a strong feature, largely due to differences in crop and nutrient management practices by differently resource-endowed farmers (Mtambanengwe and Mapfumo, 2005; Zingore *et al.,* 2007). Variation of parent materials from which the soils are derived and landscape position also define soil fertility status and productivity potential. Further details on site characterization are in Chapter 3.

5.2.2 Field sites selection procedure

Details of field sites selection procedures are given in Chapter 3, section 3.2.1 and field sites were selected as follows.

- Field Type 1: fields with ≤4 g C kg^{-1} soil
- Field Type 2: fields with 4-6 g C kg^{-1} soil
- Field Type 3: fields with >6 g C kg^{-1}

This initial work established that 70% of the sampled fields had SOC ranging from 2.4–6 g C kg^{-1} that was strongly linked to clay content (Fig. 5.1 a, b). This made it difficult to get sites that had similar clay content but significantly different in SOC content, as originally intended for site selection. The fields were subsequently divided into three soil fertility domains based on SOC, using modified guidelines developed by Zingore et al. (2011) (Fig. 5.1 c).Three experimental sites were then strategically selected, targeting these three field types on the same landscape and within a 1 km radius.

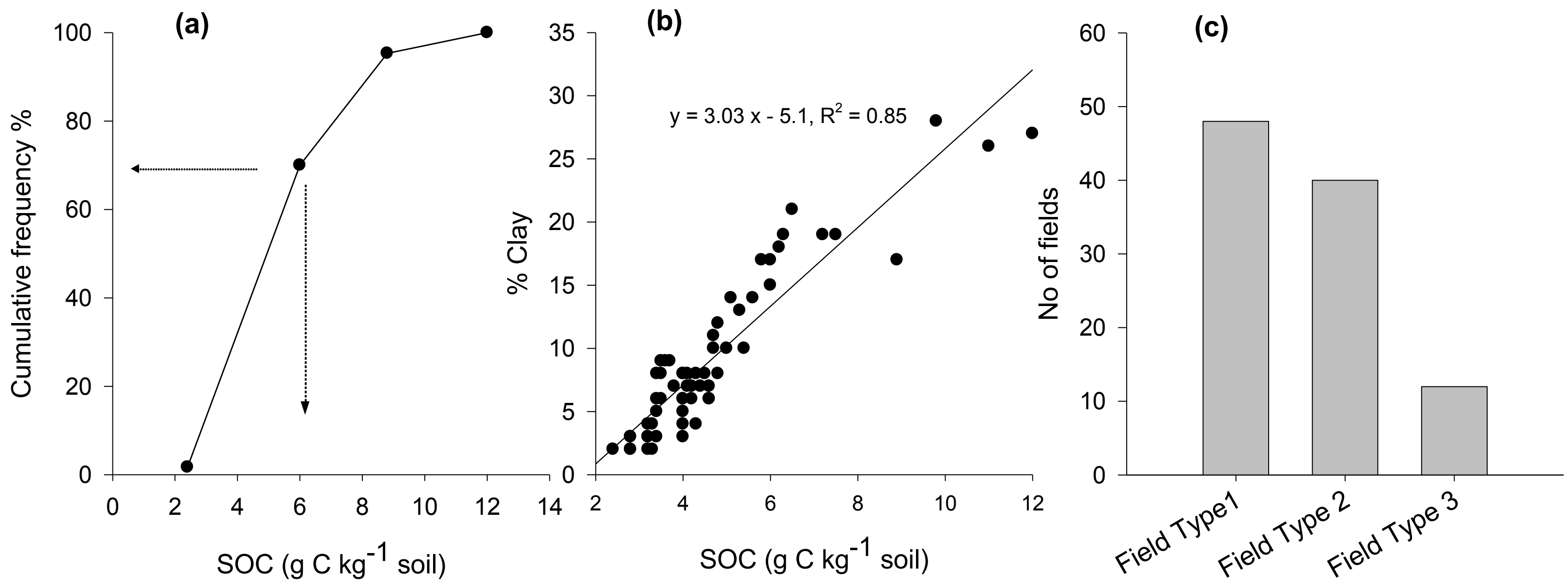


Figure 5.1 Soil organic carbon versus cumulative frequency of farms (a) soil organic carbon versus clay content across 60 fields (b) and number of farms according to soil fertility domains (c)

5.2.3 Characterization of soils for experimental sites

The detailed methodology and laboratory procedures for soil analysis are found in Chapter 3 section 3.3. The three experimental sites had SOC ranging from 3.5–8.9 g C kg^{-1} soil and clay content ranging from 4–19 %. The soils were mainly acidic with low P and N contents (Table 5.1).

5.2.4 Experimental treatments and field procedures

The experimental sites were tilled using ox-drawn ploughs to a 0-20 cm depth following the first rains in November, 2011. The experiment consisted of seven treatments, that were sole or combinations of cattle manure, NPKS-based fertilizers, micronutrients and lime, including an unfertilized control (Table 5.2).The treatments were arranged in a randomized complete block design with three replicates, on plot sizes of 4.5 m x 5 m. The same plots and experimental design were used in both years of the study. Cattle manure used across the three sites was sourced from the cattle pen of one of the host farmers, to avoid confounding effects due to variable manure quality as this is known to be variable across farms due to feeding regimes and manure handling practices (Mugwira and Murwira, 1997). The manure was applied in the planting furrows at 5 t ha^{-1} for two consecutive years with associated nutrient inputs as given in Table 5.3.

Table 5. 1 Physical and chemical properties of soils sampled from the 0-20 cm depth at experimental sites, Hwedza, Eastern Zimbabwe

Site/ soil fertility domain	Sand (%)	Clay (%)	Organic C (g kg^{-1})	Available P(mg kg^{-1})	Soil pH	Total N (%)	Ca	Mg	K
							cmol $_{(+)}$ kg^{-1}		
Field type 1 (≤4 gC kg^{-1} soil)									
Chingwa	94	4	3.5	3	4.4	0.03	0.31	0.18	0.15
Field type 2 (>4 -6. g C kg^{-1} soil)									
Chinhengo	80	10	5.4	7	4.9	0.04	0.79	0.29	0.43
Field type 3 (> 6 g C kg^{-1} soil)									
Muhwati	65	19	8.9	10	5.2	0.06	0.98	0.43	0.48

Table 5.2 Manure quality used over two years in Dendenyore, Hwedza

Cropping year	Total N (%)	Total P (%)	Total C (%)	Total Zn (mg kg^{-1})	Ca	Mg	K	Manure C:N ratio	N added through 5 t ha^{-1} manure ($kg\ ha^{-1}$)	P added through 5 t ha^{-1} manure ($kg\ ha^{-1}$)
					%					
Year 1	0.90	0.22	23.3	36	0.85	0.07	0.56	25.9	45	11.0
Year 2	0.83	0.21	22.1	29	0.70	0.05	0.42	26.6	42	10.5

Dolomitic lime, with a relative neutralizing value of 84 %, was applied at 1.5 t ha^{-1} to the appropriate plots during the first year only. A low lime application rate was used to achieve a balance in soil acidity amelioration and availability of micronutrients (Harmsen and Vlek, 1985; Nascimento *et al.,* 2007). Manure, lime, and P, K, and S were all applied prior to planting maize, and mixed with soil using hand hoes. A portion of N and the bulk of the Zn were applied prior to planting as well. Nitrogen, P, K, S, and Zn were applied at 20, 30, 60, 30, and 8 kg ha^{-1}, respectively, at planting as a combination of basal fertilizers (NPKS compound fertilizer, muriate of potash, single super phosphate, and zinc sulphate). Single super phosphate and muriate of potash were used to balance P and K application, respectively. Relatively high rates of P, K, and S were applied to enable estimation of water-limited yields under non-PKS limiting conditions for the three soil fertility domains. Sulphur was an integral component of most of the fertilizer materials that we used, and it was difficult to adequately control for the element. In addition to Zn from zinc sulphate, other micronutrients (Cu, B, and Mn) were added through a commercial foliar fertilizer once per season at anthesis stage to address possible deficiencies, at application rates not exceeding 0.3 kg ha^{-1} (Table 5.2). In addition to 20 kg ha^{-1} N at planting, two top dressing N applications through ammonium nitrate (50 kg ha^{-1} each) were planned based on rainfall and soil moisture in season.

Maize was planted at each of the three sites on 3 Dec. 2011 (Year 1) and 5 Dec. 2012 (Year 2). The maize was planted at 0.9 m inter-row and 0.25 m intra-row spacing, using two seeds per planting station. Two weeks after emergence, the plants were thinned to one plant per station, resulting in a uniform plant density of 44500 plants ha^{-1}in each site and each season. The variety used was SC513, which is recommended for agro-ecological conditions similar to that of Wedza district. SC513 is a medium maturity hybrid (135 days) with a yield potential of about 8 to 9 t ha^{-1}. Top dressing of 50 kg ha^{-1} N for Year 1 was done on the 14 Jan. 2012, and 16 Jan. for Year 2. Recommendations from the Zimbabwe Fertilizer Company (ZFC) are the first top dressing should be applied at 3 weeks after emergence (W.A.E) and the second six weeks WAE. Another study by Piha. (2003) also showed that fertilizer must be applied at 4 W.A.E and 8 W.A.E. but rainfall proved to be a limiting factor hence the delay in top-dressing. The experiments were manually weeded three times during each cropping cycle to eliminate competition for water and nutrients between maize and weeds. Harvesting was carried out between 28-30 Apr. and 2-3 May, during Years 1 and 2, respectively.

5.2.5 Maize yields and nutrient uptake determination

At maturity, maize plants were harvested from net plots of 2 central rows by 2 m long (3.6 m^2). The cobs were sun dried in perforated polythene bags over 10 days, shelled and grain yield determined using a digital scale. The grain moisture content was then determined and averaged for three sub-samples per plot using a John Deere SW moisture tester. At the time of moisture determination, the moisture content of maize grain ranged between 14-16%. All the maize yields are reported at 12.5% moisture content, the standard moisture content acceptable for grain marketed for much of southern Africa. Maize stover for each net plot was weighed in the field using a digital field scale, and sub-samples were taken to the lab for further drying and moisture correction. For determination of N, P, K and Zn, sub samples of grain and stover were first ground to 2 mm, and digested using a nitric acid and 50 % hydrogen peroxide mixture. These were then analysed in the laboratory using standard methods (Anderson and Ingram, 1993**.**

Table 5. 3 Experimental treatments and fertilizer materials used at the three experimental sites in Eastern Zimbabwe

Treatments	Target nutrient application rates†
1. Control (no amendment added)	None
2. NPKS fertilizer only	120 kg ha^{-1} N + 30 kg ha^{-1} P + 60 kg ha^{-1} K + 30 kg ha^{-1} S
3. NPKS fertilizer + Zn-micromix††	120 kg ha^{-1} N + 30 kg ha^{-1} P + 60 kg ha^{-1} K + 30 kg ha^{-1} S + 8 kg ha^{-1} Zn + micronutrient solution
4. Manure only	5 t $ha^{1}year^{-1}$ cattle manure for 2 consecutive years
5. NPKS fertilizer + manure	120 kg ha^{-1} N + 30 kg ha^{-1} P + 60 kg ha^{-1} K + 30 kg ha^{-1} S +5 t ha^{-1} $year^{-1}$ manure for 2 consecutive years
6. NPKS fertilizer + manure + Zn-micromix	120 kg ha^{-1} N + 30 kg ha^{-1} P + 60 kg ha^{-1} K + 30 kg ha^{-1} S+ 5 t ha^{-1} $year^{-1}$ manure for 2 consecutive years + 8 kg ha^{-1} Zn + micronutrient solution
7. NPKS fertilizer + lime + Zn-micromix	120 kg ha^{-1} N + 30 kg ha^{-1} P + 60 kg ha^{-1} K + 30 kg ha^{-1} S + 1.5 t ha^{-1} $CaMgCO_3$ during Year 1 + 8 kg ha^{-1} Zn + micronutrient solution

† Under 'normal rainfall' 120 kg ha N would be applied. In this study only 70 kg ha N could be applied due to prolonged mid-season dry spell

††Zn-micromix: combination of 8 kg ha^{-1} applied at planting as zinc sulphate, and foliar application at anthesis of a commercial micronutrient foliar solution containing 0.02 % Cu, 0.03 % B, 0.06 % Mn, applied at 50 L ha^{-1}, to result in application rates of 100 g ha^{-1} Cu, 150 g ha^{-1} B, and 300 g ha^{-1} Mn.

5.2.6 Determination of N and P agronomic use efficiencies and rainfall water productivity

Agronomic efficiencies for N (or P) are ideally determined as the difference between the grain yield of crop with N applied and grain yield in control without N, divided by the amount of N applied:

$$AE_N = \frac{Grain\ yield\ with\ N\ applied\ (NPKS) - grain\ yield\ with\ no\ N\ applied\ (PKS)}{Amount\ of\ N\ applied} \quad \text{EQ I}$$

Since this study did not include P-K-S or N-K-S treatments to apply the above equation, we modified the equation to compare the absolute control, which results in higher AE values.

$$AE_N = \frac{Grain\ yield\ with\ N\ applied\ (NPKS) - grain\ yield\ with\ no\ fertilizer}{Amount\ of\ N\ applied} \quad \text{EQ II}$$

Rainfall water productivity (kg grain mm^{-1} rainfall, RWP) was used as a proxy for water use efficiency for the different nutrient management strategies. During both cropping seasons, daily rainfall was recorded using two rain gauges that were situated within 2 km from the 3 experimental sites (Figure 4.1, Chapter 4). Rainfall for these two locations was averaged to get the monthly and seasonal rainfall for the area. The data was then used to compute rainfall water productivity for the different treatments and sites as follows:

$$\text{Rainfall water productivity} = \frac{\text{Maize grain yield (kg ha}^{-1})}{\text{Total rainfall (mm)}} \qquad \text{Equation III}$$

5.2.7 Statistical analyses

Nutrient management and site effects on maize grain yields and nutrient uptake were examined using a general analysis of variance (ANOVA) with Site, Treatment, and Year as factors, using the GENSTAT version 14 statistical package (Lawes Agricultural Trust, Rothamsted Experimental Station, U.K). Site and treatment were fixed effects. However, while year is a random effect, the statistical analysis was conducted with Year as a fixed effect to get an indication of the importance of interactions of Year, Site, and Treatment. Where appropriate, least significant differences (LSDs) were used to separate means at $P < 0.05$.

5.3 Results

5.3.1 Rainfall distribution and N management

The first and second season's total rainfall were 780 mm and 891 mm, respectively, which were both comparable to the long term average of 825 mm for the area (Figure 4.1, Chapter 4). In spite of this, rainfall distribution was skewed for both seasons, with flooding and drought episodes occurring during the cropping seasons. For example, during Year 1, over 400 mm of rainfall were received within the month of December whilst during Year 2, the same trend was observed in the month of January. Severe dry spells lasting for up to 4 weeks were experienced during both cropping seasons. In line with the experimental protocol, the second 50 kg ha^{-1} top dressing N fertilizer was therefore withheld.

5.3.2 Maize productivity across soil fertility domains

Maize productivity was significantly influenced by site and treatment ($P < 0.01$; Figure 5.2), with maize grain yield site means over the two years of 1.47, 3.09, and 3.18 t ha^{-1}, for Fields Types 1, 2, and 3, respectively, indicating insignificant separation between Field Types 2 and 3. There was a significant Site x Treatment interaction ($P < 0.01$) but there was no significant interaction for Site x Treatment x Year. During the 2011/12 season, maize grain yield for the control treatment on Field Type 1 was a paltry 0.28 t ha^{-1} (Figure 5.2a). The control treatments for Field Types 2 and 3 had both significantly higher maize yields than Field Type 1, of 0.87 and 1.12 t ha^{-1}, respectively (Figure 5.2b;c). Application of cattle manure only on Field Type 1 did not result in any significant differences between the control and manure treatment. However, on Field Types 2 and 3, application of manure resulted in significant increases in maize yields over the control. Also, on Field Types 2 and 3, treatments that contained manure + NPKS had significantly higher yields than the NPKS treatment (Figure 5.2).

During Year 2, the NPKS + lime + Zn-micromix treatment had the highest maize grain yields of 2.24 t ha^{-1} for all treatments within Field Type 1, significantly surpassing the NPKS + manure + Zn-micromix that had a mean yield of 1.65 t ha^{-1} (Figure 5.2d). In contrast, the NPKS + lime + Zn-micromix treatment did not result in such a marked effect on maize yields for Field Types 2 and 3. Application of manure alone significantly increased ($P < 0.01$) maize grain yields over the control on Field Types 2 and 3 (Figure 5.2e, f). With manure only, maize yields increased from 1.2 t ha^{-1} to 1.73 t ha^{-1} for Field Type 2 and from 0.99 t ha^{-1} to 1.87 t ha^{-1} for Field Type 3 (Figure 5.2e, f). Generally, treatments that contained NPKS + manure consistently had yields that ranked in the highest yielding group. Micronutrient addition did not appreciably influence maize grain yields over all sites for both cropping seasons.

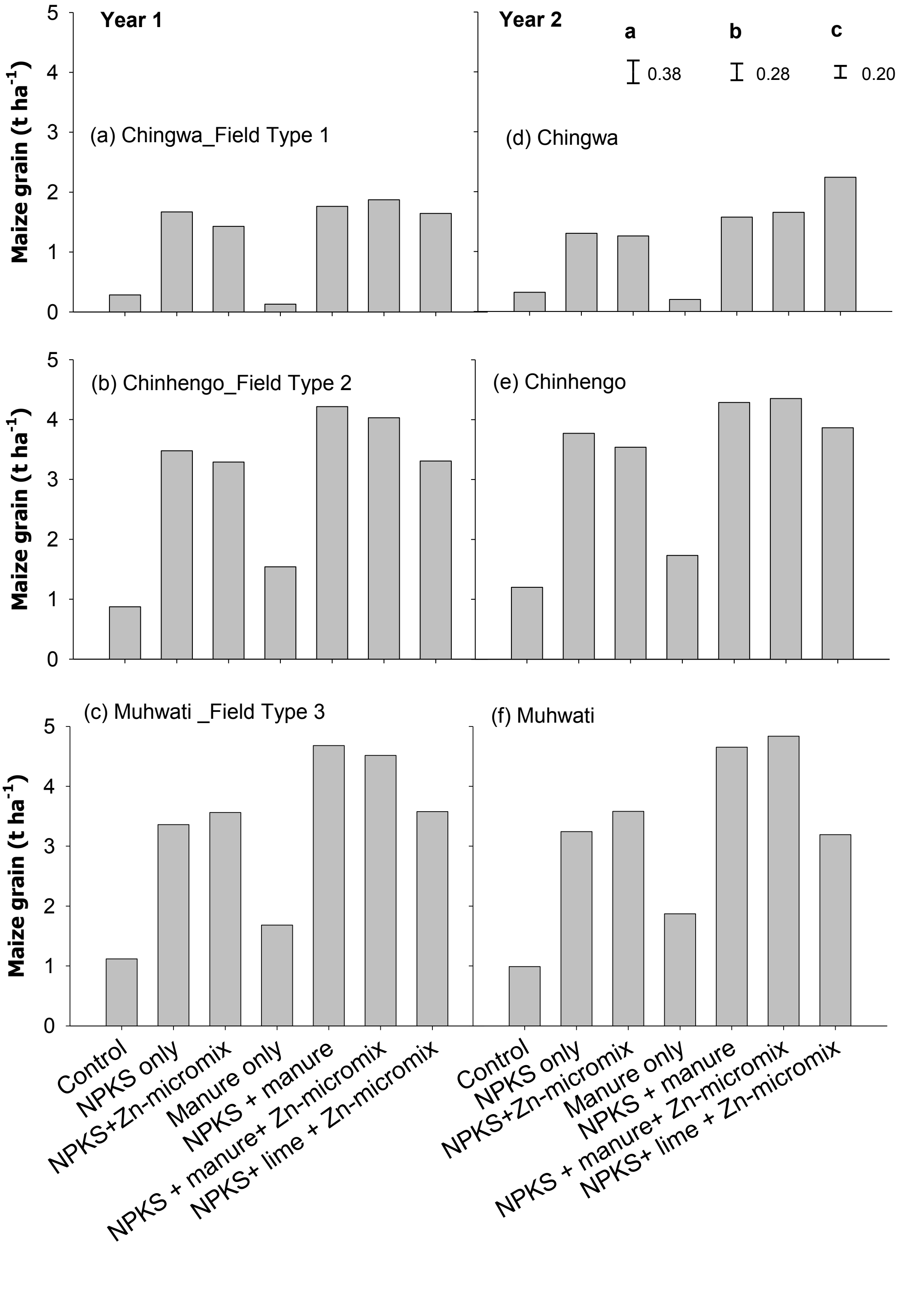


Figure 5.2 Maize grain and stover yields as influenced by nutrient management across three on-farm sites for the 2011-2013 cropping seasons in Dendenyore Ward, Hwedza, Zimbabwe

Error bars are LSDs for different factors (a) treatment, (b) site, and (c) year

5.3.3 Nitrogen P, K and Zn uptake by maize

Total N, P, K and Zn uptake by maize for different treatments were determined through analyses of both grain and stover for N, P, K and Zn concentration and multiplying these by the respective yields. Generally, the internal concentration of N for grain varied little, ranging between 1.4 and 1.7%, while N content in stover ranged between 0.56 and 0.80%. Phosphorus concentration in grain ranged from 0.23 to 0.30% across sites and treatments, while stover P content averaged 0.19%, with little variation. Zn concentration in grain increased from an average of 0.17 mg kg^{-1} for treatments that did not receive any Zn fertilizer to an average of 0.25 mg kg^{-1} when Zn was added as a combination of basal and foliar applications. During the 2011/12 season, total N uptake values for the control treatment were 6.9, 20.2 and 26.8 kg ha^{-1} for Field Types 1, 2 and 3, respectively, with the corresponding P uptake of 1.4, 4.2 and 5.5 kg ha^{-1} (Table 5.4). In general, the highest N, P, K, and Zn uptake was with either the NPKS + manure treatment or the NPKS + manure + Zn-micromix treatment, which were themselves not significantly different (Tables 5.4 and 5.5). Nitrogen, P and K uptake for Year 2 were remarkably similar to that for Year 1, being so despite repeated application of both NPKS fertilizers and manure. Notably, with a cumulative application of 10 t ha^{-1} manure by Year 2, nutrient uptake for the sole manure treatment did not differ from the control for Field Type 1 (Table 5.5). The effect of liming on the acidic soils was not evident during Year 1 and only enhanced nutrient uptake during Year 2, and was confined to Field Type 1.

Table 5. 4 Total above ground N, P, K uptake (kg ha^{-1}) and Zn uptake (g ha^{-1}) as influenced by liming and micronutrient fertilization strategies across soil fertility domains during the first season, Hwedza, Zimbabwe

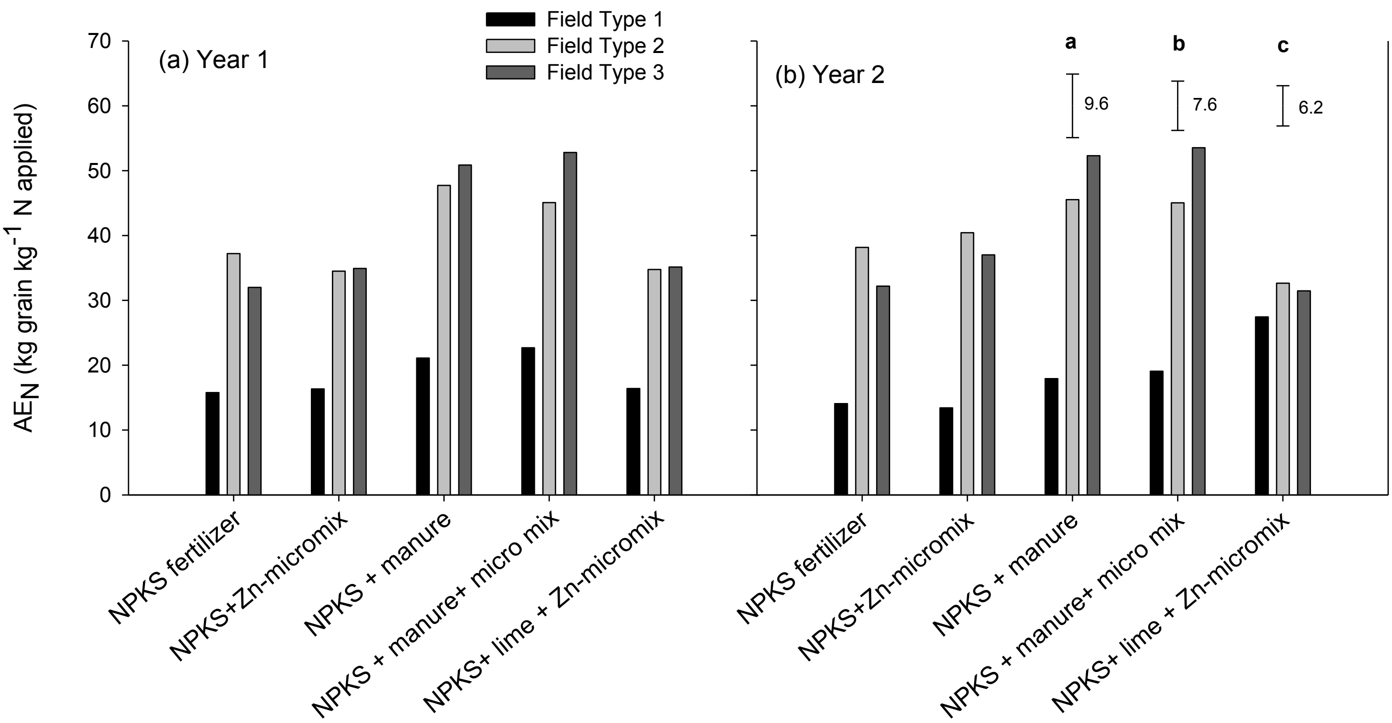
Site/soil fertility domain	Treatment	Total N Uptake	Total P Uptake	Total K uptake	Total Zn uptake
		kg ha^{-1}			g ha^{-1}
Field Type 1	Control	6.9[a]	1.4	8.4	10
(Chingwa 3.5 g C kg^{-1} soil)	NPKS	32.8	7.9	31.2	64
	NPKS+ micronutrient	31.5	9.6	31.2	79
	Cattle manure	3.0	1.6	7.6	16
	NPKS+ manure	34.7	8.7	33.8	85
	NPKS+ manure + micronutrients	33.7	8.7	36.1	85
	NPKS + lime + micronutrients	35.2	7.6	33.6	73
Field type 2	Control	20.2	4.2	17.6	34
(Chinhengo 5.4 g C kg $^{-1}$soil)	NPKS	87.9	16.1	79.8	171
	NPKS+ micronutrient	80.8	15.3	82.3	165
	Cattle manure	36.0	7.3	32.8	72
	NPKS+ manure	99.6	19.5	96.8	172
	NPKS+ manure + micronutrients	97.6	18.6	92.3	193
	NPKS + lime + micronutrients	79.5	15.5	83.2	177
Field Type 3	Control	26.8	5.5	28.6	46
(Muhwati 8.9 g C kg^{-1} soil)	NPKS	81.5	15.6	78.6	144
	NPKS+ micronutrient	88.6	16.4	84.3	162
	Cattle manure	41.7	8.4	43.5	75
	NPKS+ manure	105.8	20.3	99.8	185
	NPKS+ manure + micronutrients	106.2	20.2	95.3	196
	NPKS + lime + micronutrients	87.5	16.5	85.2	165
	LSD(0.05)	7.22	1.28	7.4	13.0

Table 5.5 Total above ground N, P, K uptake (kg ha^{-1}) and Zn uptake (g ha^{-1}) as influenced by liming and micronutrient fertilization strategies across soil fertility domains during the second season, Hwedza, Zimbabwe

Site	Treatment	Total N uptake	Total P uptake	Total K uptake	Total Zn uptake
			kg ha^{-1}		g ha^{-1}
Field Type 1	Control	7.7	1.6	8.2	12
(Chingwa 3.5 g kg^{-1} soil)	NPKS	31.7	8.1	29.2	68
	NPKS+ micronutrient	32.3	7.3	33.4	84
	Cattle manure	7.6	1.3	7.5	16
	NPKS+ manure	32.4	8.7	33.1	85
	NPKS+ manure + micronutrients	31.1	9.4	34.2	109
	NPKS + lime + micronutrients	45.8	10.8	42.1	85
Field Type 2	Control	26.6	6.2	30.9	47
(Chinhengo 5.4 g C kg $^{-1}$soil)	NPKS	77.4	19.6	72.5	152
	NPKS+ micronutrient	79.6	18.8	72.1	162
	Cattle manure	41.2	8.4	43.2	66
	NPKS+ manure	104.9	21.2	97.7	184
	NPKS+ manure + micronutrients	102.1	20.4	93.1	190
	NPKS + lime + micronutrients	75.4	14.6	74.2	168
	Control	24.8	5.2	25.5	47
Field Type 3	NPKS	80.0	15.7	83.5	161
(Muhwati 8.9 g C kg^{-1} soil)	NPKS+ micronutrient	84.9	17.3	88.2	192
	Cattle manure	40.1	7.4	40.4	76
	NPKS+ manure	101.3	21.1	98.7	189
	NPKS+ manure + micronutrients	101.9.	20.2	99.2	201
	NPKS + lime + micronutrients	84.4	16.3	89.1	188
	LSD(0.05)	7.22	1.28	7.4	13

5.3.4 Nitrogen and P agronomic efficiencies and rainfall productivity

Agronomic efficiencies for N and P ($AE_{N \text{ or } P}$) applied through mineral fertilizers were



calculated as kg grain produced per kg N or P applied, with the NPKS treatment used to evaluate the benefits of liming, addition of micronutrients or manure

Figure 5.3 Nitrogen agronomic efficiencies during Year 1 (A) and Year 2 (B), as influenced by nutrient management and soil resource base in Dendenyore, Hwedza district, Zimbabwe

Error bars are LSDs for different factors (a) treatment, (b) site, and (c) year

Nitrogen agronomic efficiencies were significantly smaller for Field Type 1 compared with Field Types 2 and 3 for both years ($P < 0.01$; Figure 5. 3). There were no significant differences between Field Types 2 and 3. During Year 1, the highest AE_N of all treatments within Field Type 1 was for the treatment NPKS + manure + micronutrients achieving 22.7 kg grain kg^{-1} N applied. This sharply contrasts with the highest AE_N of all treatments within Field Type 2 of 48.7 kg grain kg^{-1} N (NPKS +manure), and 52.8 kg grain kg^{-1} N applied for all treatments within Field Type 3 (NPKS + manure + micronutrients) (Figure 5.3a). During Year 2, the NPKS + lime treatment had the highest AE_N of 27.5 kg grain kg^{-1} N applied for all treatments within Field Type 1, compared with 47.5 kg grain kg^{-1} N for NPKS + manure for Field Type 2, and 52.5 kg grain kg^{-1} N for NPKS + manure + micronutrients for Field Type 3 (Figure 5.3b). Agronomic efficiencies for P had a trend similar to that for AE_N (Figure 5.4). Of all treatments within Field Type 1, the NPKS + manure +micronutrients had the highest AE_P of 39.7 kg grain kg^{-1} P applied, compared with highest AE_P of 83 and 92 kg grain kg^{-1} P applied for all treatments within Field Types 2 and 3, respectively, during Year 1 (Figure 5.4a). On Field Type1, the AE_P

significantly increased ($P<0.01$) from 24 kg grain kg^{-1} P for Year 1 to 48 kg grain kg^{-1} P for Year 2, as a result of lime that had been applied during Year 1.

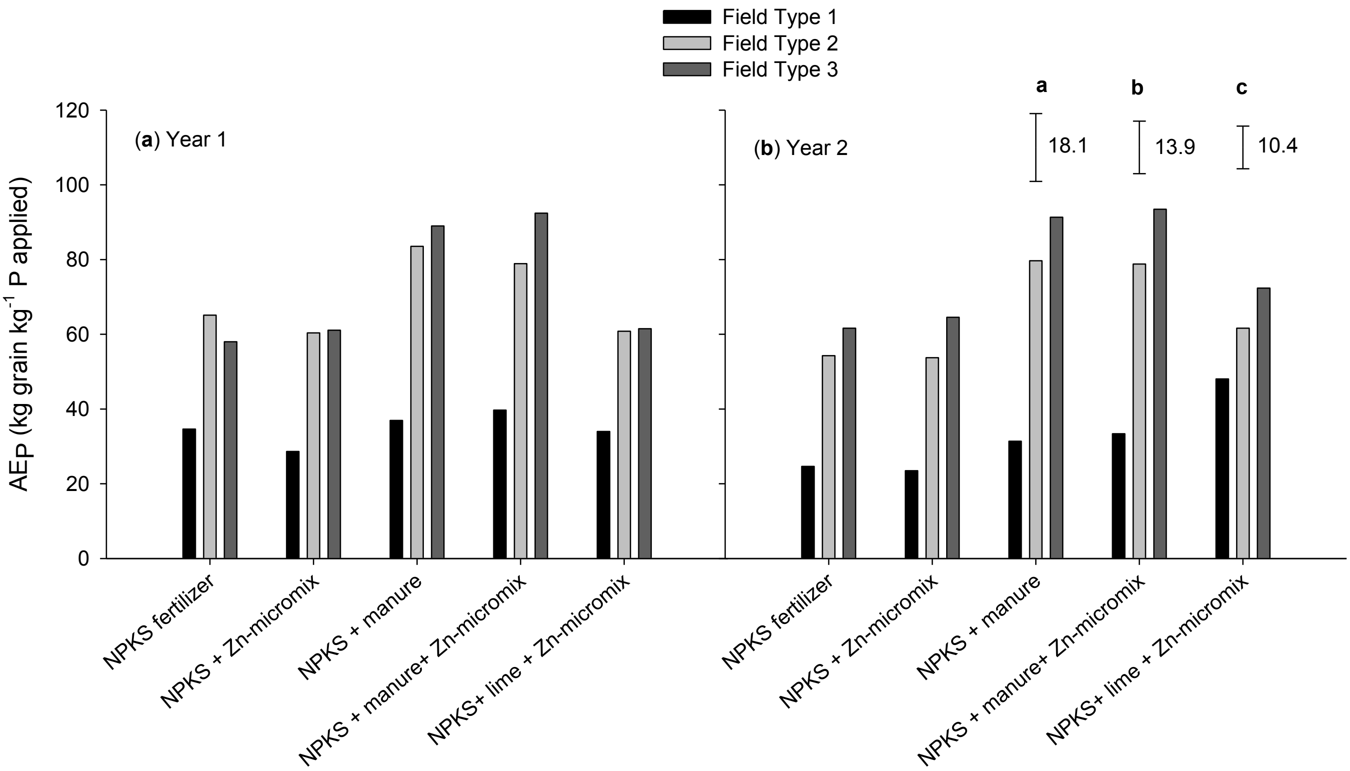


Figure 5.4 Phosphorus agronomic efficiencies during Year 1 (A) and Year 2 (B), as influenced by nutrient management and soil resource base in Dendenyore, Hwedza district, Zimbabwe.

Error bars are LSDs for different factors (a) treatment, (b) site, and (c) year

5.3.5 Rainfall water productivity

Rainfall water productivity, RWP, (kg grain mm^{-1} rainfall) was a function of both soil fertility status and nutrient management and was consistent across seasons. For both seasons, RWP ranged from 0.22–2.4 kg grain mm^{-1} rainfall for Field Type 1 and between 1.1–5.4 kg grain mm^{-1} rainfall for Field Types 2 and 3 (Figure 5.5).

5.3.6 Short-term changes in soil chemical properties

Before experimentation, soil samples were taken from the 0–20 cm layer from the three sites and analyzed for SOC, total N, available P, pH and the bases Ca, Mg, and K (See section 3.3). At the time of harvesting the Year 2 crop, soil sampling was also done according to treatments, and analysed for the same parameters. There were no measurable changes for SOC and total N, including those plots that received cumulative 10 t ha^{-1} manure (Table 5.6). At the end of Year 2, available P had increased significantly ($p< 0.05$) across all sites for all treatments that received NPKS and/or manure. For Field Types 1 and 2, available P increased from baseline concentrations of 3.2 and 5.1 mg kg^{-1} to averages of about 6.5 and 10 mg kg^{-1}, respectively, with NPKS application for two consecutive seasons. The corresponding increases for Field Type 3 were from a baseline of 9.6 to about 14 mg kg^{-1}. Both manure and lime application did not significantly increase soil for Field Types 2 and 3, while significant pH changes of 0.5 pH units were realized for Field Type 1. Both exchangeable Ca and Mg increased significantly for all treatments that received manure and lime.

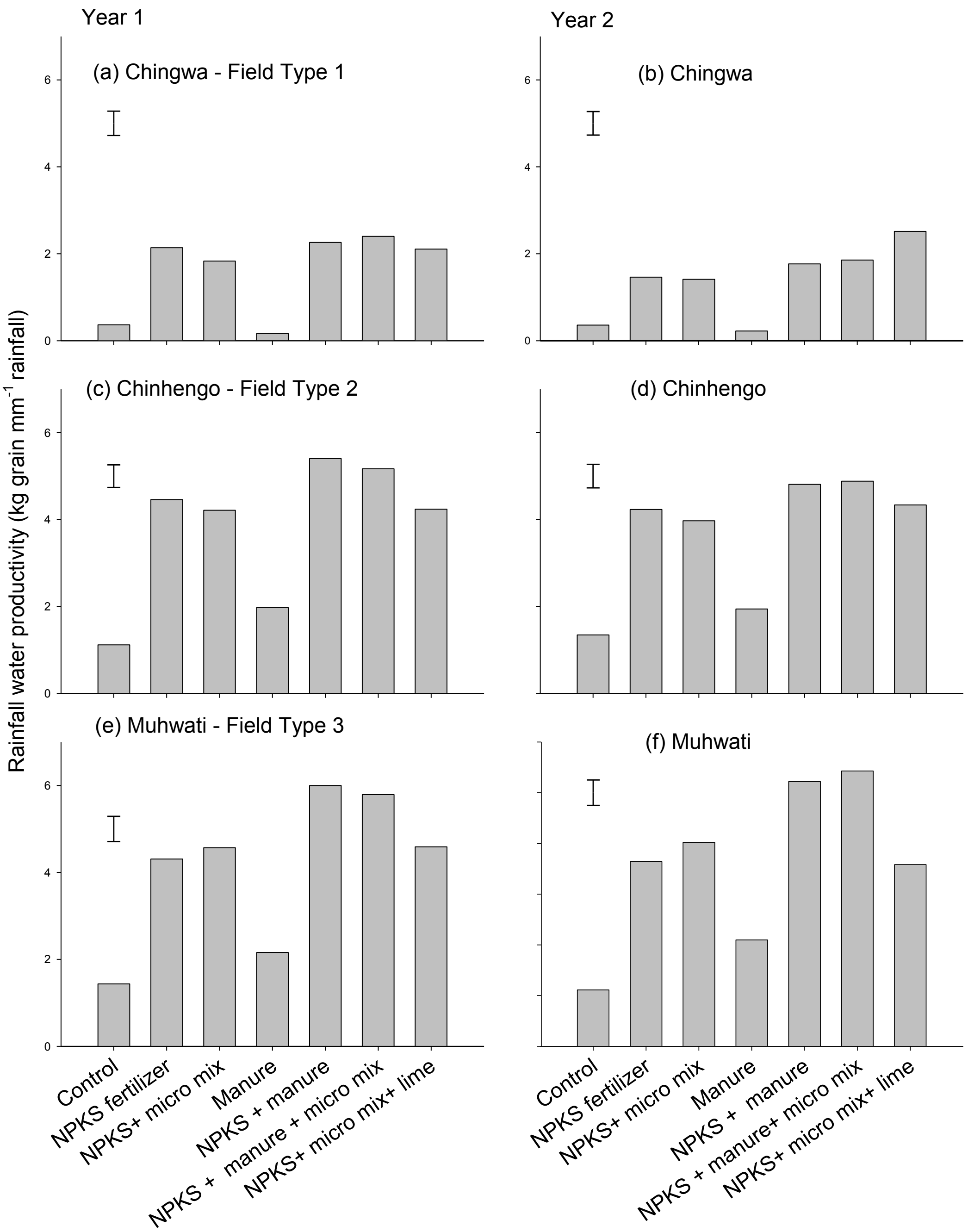


Figure 5.5 Water productivity (kg grain mm^{-1} rainfall) for Year 1 at Chingwa, Chinhengo and Muhwati sites (a,b,c) and Year 2 (c,d,e), as influenced by nutrient management for the three experimental sites belonging to different soil fertility domains, Dendenyore Ward

Table 5.6 Baseline soil chemical characteristics at the end of the second cropping season on three soil fertility domains, Dendenyore, Hwedza

Site/treatments	SOC (%)	Total N (%)	pH	Available P (mg kg^{-1})	Exchangeable bases (cmol$_c$ kg^{-1}) Ca	Mg	K
Field Type 1: Chingwa							
Baseline conditions	*0.35*	*0.03*	*4.4*	*3.2*	*0.31*	*0.18*	*0.14*
Control	0.34	0.03	4.3	2.8	0.28	0.17	0.12
NPKS fertilizer	0.34	0.04	4.2	6.4	0.26	0.19	0.12
NPKS + micromix	0.36	0.03	4.2	6.6	0.41	0.21	0.13
Manure	0.34	0.04	4.5	3.4	0.23	0.24	0.13
NPKS + manure	0.35	0.03	4.6	7.4	0.48	0.23	0.21
NPKS + manure + micromix	0.35	0.04	4.6	6.5	0.51	0.24	0.22
NPKS + micromix + lime	0.34	0.04	4.9	6.8	0.54	0.26	0.22
LSD(0.05)	0.02	0.01	0.2	1.0	0.2	0.08	0.06
Field Type 2: Chinhengo							
Baseline conditions	*0.54*	*0.04*	*4.9*	*5.1*	*0.79*	*0.29*	*0.43*
Control	0.54	0.04	4.8	4.9	0.75	0.28	0.41
NPKS	0.53	0.04	4.8	10.4	0.74	0.32	0.48
NPKS + micromix	0.55	0.04	4.8	9.5	0.78	0.31	0.49
Manure	0.54	0.03	5.1	5.9	0.88	0.34	0.35
NPKS + cattle manure	0.54	0.03	5.2	9.8	1.22	0.32	0.47
NPKS + manure + micromix	0.55	0.04	5.2	10.5	1.21	0.38	0.46
NPKS + manure + lime	0.54	0.04	5.3	10.1	1.28	0.39	0.45
LSD(0.05)	0.02	0.02	0.2	1.2	0.10	0.11	0.09
Field Type 3: Muhwati							
Baseline conditions	*0.89*	*0.06*	*5.2*	*9.6*	*0.98*	*0.43*	*0.48*
Control	0.90	0.05	5.1	9.1	0.87	0.43	0.49
NPKS	0.89	0.06	5.2	14.2	0.94	0.41	0.52
NPKS + micromix	0.90	0.06	5.2	15.4	1.31	0.41	0.59
Manure	0.89	0.06	5.3	10.8	1.67	0.51	0.48
NPKS + manure	0.90	0.07	5.2	14.5	1.75	0.64	0.53
NPKS + manure + micromix	0.91	0.07	5.3	13.2	1.77	0.63	0.61
NPKS + manure + lime	0.90	0.06	5.4	13.5	1.74	0.45	0.56
LSD(0.05)	0.02	0.02	0.3	1.8	0.08	0.12	0.08

5.4 Discussion

5.4.1 Soil chemical and physical spectrum across farms

Physical and chemical analyses of soil samples across 60 farms indicated that the majority of the farms had low SOC content that was correlated with clay content (R^2 =0.85; Figure 5.1).This is in line with previous studies (Six *et al.,* 2002; Zingore *et al.,* 2011). While soils with low clay content would naturally have poor cation exchange capacity, the low water holding capacity dimension poses serious problems for rain-fed systems that have characteristically erratic rainfall distribution. In this study, the combination of dry spells and soils with poor water holding capacity resulted in the available soil moisture being depleted faster, and subsequently the planned second N top-dressing was withheld during both seasons. This tactical rainfall-responsive management strategy of top dressing N also advocated by Piha (1993), may make N fertilizer use more attractive to smallholder farmers in drought prone environments.

5.4.2 Maize productivity and response to nutrient application

Maize productivity was lowest in the Field Type 1 (< 4 g SOC kg^{-1} soil) category with yields as low as 0.22 t ha^{-1} without added nutrients and maximum yields not exceeding 2.3 t ha^{-1} for the NPKS + manure treatment (Figure 5.2). Over the two cropping seasons, application of manure alone on Field Type 1 did not result in increased yields, suggesting that the use of manure with nutrient composition as was used in this study, will not improve maize productivity on poor soils in the short term. Unfortunately, most of the manure produced on smallholder farms has nutrient composition comparable with the manure that was used in this study

(Chikowo *et al.,* 1999; Mugwira and Murwira, 1997; Murwira and Kirchmann, 1993; Palm *et al.,* 2001), making these findings broadly applicable to this region. Often, smallholder farmers have sustained low maize production levels by managing soil fertility through application of a combination of small quantities of livestock manure, compost and spreading nutrient-rich *termitaria* soils around the crop fields (Mtambanengwe and Mapfumo, 2006). Although concentration of nutrients in these resources is low, the little macro- and micronutrients that become available avert acute nutrient deficiencies, making production of modest yields possible. The treatments that contained manure + NPKS consistently had yields that ranked in the highest yielding group. In the long term, this fertilization strategy may result in improved SOC and improved soil pH as manure application has a liming effect (Chikowo *et al.,* 2010; Mtambanengwe *et al.,* 2006; Nezomba *et al.,* 2014; Vanlauwe *et al.,* 2011; Zingore *et al.,* 2008). However, although many farmers in this region apply manure, the quantity applied may not be sufficient to raise SOC (Rufino *et al.,* 2011), making the 'modest' application of 10 t ha^{-1} manure in two years unattainable in many cases. Investments in technologies that will have benefits but only in the medium to long-term (4 years +) are seldom prioritized by farmers.

A key finding of this study was that Field Type 3 (> 6 g C kg^{-1} soil) did not give significantly different maize response to nutrients applied, relative to results for Field Type 2 (>4-6 g C kg^{-1} soil (Tables 5.4 and 5.5; Figures 5.3 and 5.4). This has practical implications for how farmers can efficiently target their limited resources. The first implication being that farmers should target their inputs to soils with > 4 g C kg^{-1} of soil or alternatively raise SOC levels to meet the minimum threshold of > 4 g C kg^{-1} soil. Raising soil organic carbon on sandy soils is difficult as it is prone to decomposition due to lack of clay. Long terms studies over nine years to improve fertility on sandy soils with minimum additions of 5 t ha^{-1} of manure annually were not promising with little increase in SOC and yields (Rusinamhodzi *et al.,* 2013). Translated to the smallholder farming scenario this would mean a farmer would need to invest inputs for over a decade before there is a breakthrough of which it would be highly unlikely if there are more fertile pieces of land. Research has also suggested that when SOC levels are below 10 g C kg^{-1} soil it may not be possible to achieve maximum yields (Kay and Angers, 1999). A threshold value for SOC for maximum crop production is difficult, or impossible to define as other biophysical limitations such as rainfall and soil type would influence crop response (Loveland and Webb, 2003). Concentrating organic inputs on already fertile fields could result in diminishing returns and accentuates nutrient gradients on the farms but may be practical for a farmer to produce good yields instead of spreading resources' around the farm. (Rowe, 2006)

5.4.3 Acidic soils and response to liming

Soil pH values on Field Types 1, 2, and 3 were 4.4, 4.9, and 5.2, respectively (Table 5.1), indicating strongly acidic conditions. Despite this, there was no yield response to lime application across all sites during Year 1, and response was only realized during Year 2 for the most acidic site. This was expected as usually lime reaction is slow on dry soils and it may take up to a year for a measurable change on soil pH (Helyar, 1998). Lime is also highly immobile therefore the sub layers of soil are rarely affected by it and its application to such depths is expensive and labour intensive in the smallholder context (Kidd, 2001). The Ca and Mg applied through the dolomitic lime were also expected to improve concentration of these nutrients in the soils. This study did not measure Al in the soil and perhaps not enough Al was displaced by the lime application as a rate of 1.5 t ha^{-1} lime is possibly too low for such acidic soil conditions.

Previous research has indicated that some soils in Hwedza have Al saturation of more than 20% (Dhliwayo *et al,* 1998. Perhaps both seasons were too dry during grain fill to capture the expected benefits of liming. Although lime is relatively cheap many hindrances prevent its use by smallholder farmers including transport costs due to the large quantities involved as well as lack of knowledge on its application (Nyamangara and Mpofu, 1996). Surveys to assess the levels of acidity across smallholder farms would greatly assist in establishing liming recommendations for the fertility domains. It must also be borne in mind that routine application of lime may result in very high pH causing micro-nutrient deficiencies as well as unavailability of P (Pearson, 1975). These results suggest that there remain unique nutrient imbalances that must be addressed for efficient utilization of both lime and fertilizer resources. Increased use of organic nutrient resources in the form of both livestock manure and compost is expected to address soil quality and rehabilitate function on these degraded soils, which in turn offer opportunities for enhanced use efficiency of mineral fertilizers.

5.5 Conclusions

The study has revealed that response to nutrient application is strongly linked to the initial soil fertility condition, with SOC < 4 g kg^{-1} consistently associated with poor nutrient use efficiencies. There were no differences in response to fertilizer, lime or manure application between soils classified as Field Type 2 and 3, based on SOC content. It may be that above a threshold of 4 g C kg^{-1}soil, further characterization by SOC content does not provide predictive power, and attention needs to be shifted to evaluating SOC fractions or related soil quality parameters. This has practical implications regarding how farmers with limited nutrient resources efficiently target and apply nutrient. This study provided evidence that SOC levels

>4g C kg^{-1} meets the basic requirements for producing maize yields > 4 t ha^{-1}. Concentrating organic inputs on already fertile fields results in diminishing returns and accentuates nutrient gradients on the farms. These results suggest that there remain unique nutrient imbalances that must be addressed for efficient utilization of both lime and fertilizer resources.

CHAPTER 6

APPLICATION OF A DECISION SUPPORT TOOL (NUTRIENT EXPERT) TO ASSESS PROFITABILITY OF RESOURCE USE ON FARMS IN HWEDZA, ZIMBABWE

Abstract

The highly heterogeneous environments and diverse socio-economic backgrounds of smallholder farmers in Sub Saharan Africa call for innovative strategies to address these various dynamics. To enable context specific solutions, research must not only address bio-physical problems but also tackle socio-economic factors for a more holistic approach. Farmers are constantly grappling with day to day decisions on how to efficiently target nutrient resources while insuring of the profitability of their current practices. The Nutrient Expert (NE) model is one such Decision Support Tool (DST) that is currently being refined to better study these systems. The NE was employed to analyse current farming practises under common scenarios prevalent on the smallholder farms and to suggest viable alternative practises where necessary. Farm typologies were defined according to previous studies into High, Medium and Low Resource endowments (HRE, MRE and LRE) respectively and the average nutrient management practises in each group analysed. Productivity across farms was mainly influenced by resource endowment with HRE farmers' attaining maize yields of 3 t ha^{-1} and LRE yields of < 1t ha^{-1}. Resource endowment was highly influential on soil fertility status and soil fertility enhancement methods employed by the respective farmer groups. In addition size of land cultivated was also strongly related to resource endowment. The NE analysis showed that fertilizer use across all resource groups was suboptimal suggesting that with current fertilizer practices none of the farmer classes could reach the attainable yield of 6 t ha^{-1}. Alternative recommendations generated showed that HRE and MRE farmer classes could double their yields and net profits by increasing fertilizer use by 50 and 100% respectively. In the event of a drought the NE suggested lower application rates in such cases. Overall findings from this study indicated that the NE has great potential as a tool to improve the targeting of nutrient resources across farmer groups as it is context specific and also makes use of biophysical data.

6.1 Introduction

Smallholder farmers in Zimbabwe are operating in highly heterogeneous systems in terms of socio-economic backgrounds and bio-physical factors (Scoones, 2001). The futility of blanket fertilizer recommendations in light of afore- mentioned circumstances is obvious as plant responses are highly variable across soil fertility gradients (Smaling *et al.,* 2002). However experimentation to get site specific recommendations is expensive and time consuming to develop in financially constrained environments. Experimental data from nutrient omission experiments or decision support tools can be used to formulate recommendations. The use of decision support tools (DSTs) offers an alternative option to blanket recommendations and empowers extension workers to advise farmers on nutrient management in a short time and at a low cost (Defoer, 2002). The Nutrient Expert (NE) is one such tool that has potential to be used by researchers and extension at different levels. However, the uptake of DSTs has not been popular in the region due to limitations such as intensive data input, lack of knowledge and limited applicability in complex agricultural systems (Bontkes and Wopereis, 2003).

The Nutrient Expert is a computer based decision support tool which may be used to quickly formulate fertilizer guidelines for hybrid maize (Pampolino *et al.,* 2012). The software makes use of information that can be provided by a farmer or an expert on past management practices, quantities of nutrients applied as well as attainable yields. Assumptions by the NE include the following:

i. Any problems on acidity and micronutrients are properly addressed
ii. Use of high yielding varieties

iii. No major damage caused by pests and diseases, and
iv. Proper placement of fertilizer is practiced

The NE for Hybrid maize for Zimbabwe follows the conceptual framework of NE applied to maize and wheat in Asia (Pampolino *et al.,* 2012). Nutrient Expert has employed site specific nutrient management concepts (SSNM) to develop strategies to manage fertilizer N, P, and K management (Pampolino *et al.,* 2012). Site specific nutrient management is a set of nutrient management principles which aims to supply a crop’s nutrient requirements tailored to a specific field or growing environment (Witt *et al.,* 1999). The major aims of SSNM include (a) taking into account indigenous nutrient sources as well as added nutrients in crop residues and manures; (b) apply fertilizer at optimal rates and at critical growth stages to meet the deficit between the nutrient needs of the crop and the indigenous nutrient supply (IRRI, 2011).

Fertilizer requirements for a field or location is estimated from the expected yield response to each fertilizer nutrient, which is the difference between the attainable yield and the nutrient-limited yield (Chapter 4). In SSNM, the N, P and K requirements are based on the relationship between the balanced uptake of nutrients at harvest and grain yield (Witt *et al.,* 1999; Buresh *et al.,* 2010), which are predicted using the widely used quantitative evaluation of the fertility of tropical soils (QUEFTS) model (Smaling and Janssen, 1993). Since the amount of nutrients is directly correlated to its yield, the yield response is indicative of the nutrient deficit which must be supplied by fertilizers. The objective of the study was to evaluate the profitability of current nutrient management methods and other common scenarios prevalent on smallholder farms in Zimbabwe.

6.2 Methodology

6.2.1 Study area and farmer selection

The study site for analysis of farmers' soil fertility practices was Dendenyore Ward, Hwedza. A detailed description of the area has been given in Chapter 3. The framework for categorisation of farmers was guided by earlier work on farm typologies and divided the farmers into three groups (Mtambanengwe and Mapfumo, 2005; Zingore *et al.,* 2011). The resource groups were as follows: High Resource Endowment (HRE), Medium Resource Endowment (MRE) and Low Resource Endowment (LRE). Baseline surveys provided attainable yields for the farmer categories. Estimates for attainable yields were developed by factoring in yield reducing factors such as drought and soil fertility constraints. Average soil fertility management practices for each class were then analysed by NE. The four common steps which require information are as follows:

i. Current nutrient management practice: Includes famers management of fertilizer inputs yield as well as field size
ii. Planting density: plant population per unit area
iii. Site characteristics : This includes soil fertility rating, past management practises and rainfall amount
iv. Profit analysis: Costing of labour, seed and fertilizer

6.2.2 Analysis of current farmer management practises and other common scenarios

(i) Analysis of the average current fertilizer management practices (Table 6.1) was carried out to show how nutrient use can be optimised across various field types with alternative recommendations from the NE. Since soil fertility is a function of resource endowment the analysis was based on a positive correlation between resource endowment and soil fertility (Mtambanengwe and Mapfumo, 2006; Masvaya, 2010; Zingore *et al.,* 2007; 2011). Using soil organic carbon as a proxy for soil fertility low soil fertility was defined < 4 g C kg^{-1} soil, medium fertility 4 – 6 g C kg^{-1} soil and high fertility as > 6 g C kg^{-1} soil. Therefore, HRE group had fertile fields while LRE had poor fertility fields with MRE on the medium fertility fields. The NE also generated an economic analysis to show gross margins of current practices versus recommendations from the NE. The current farmer fertilizer practices on the type of soil were inputted in the decision support tool to generate recommendations and analyse their profitability.

Table 6. 1 Average fertilizer application rates according to farmer resource endowment for Dendenyore Ward, Hwedza, Zimbabwe

Nutrient (kg $ha^{-1)}$	LRE	MRE	HRE
Nitrogen	20	54	80
Phosphorous	7	14	20
Potassium	4	7	10

[1] HRE High resource endowment [2] MRE Medium resource endowment

[3] LRE Low resource endowment

(ii) Optimised nutrient practice

In this scenario, the NE was applied to predict the best fertilizer recommendation required to meet attainable yields for each of the three farm resources groups at the two sites. Attainable yields were determined by the NE depending on the risks/ constraints in the growing environment. Data from nutrient omission experiments was used to estimate attainable yields in an environment where water was not limiting.

(iii) Integrated nutrient management practices

This option evaluated the combinations of manure with fertilizers. However for the LRE group the option could not be analysed as they do not have access to manure.

(iv) Droughts are a common risk in Hwedza district therefore a scenario analysis of possible management options practiced by farmers in a drought year was carried out.

Table 6.2 shows the values inputted into the Nutrient Expert to calculate profitability. Labour requirements are proportional to the size of the farm according to resource endowment and standard rates are therefore provided.

Table 6.2. Parameters used to calculate gross and net profit for various nutrient management scenarios using the Nutrient Expert for Hybrid Maize.

A. Gross Profit Analysis	Unit	Cost \$ USD
Cost of seeds	\$USD kg^{-1}	2.20
Ammonium Nitrate	\$USD kg^{-1}N	1.75
P-K-S (basal fertilizer)	\$ USD kg^{-1} P	3.98
Price of maize	\$USD t^{-1}	260.00
B Net Profit Analysis		
1 Labour cost variables		
Land preparation	4 man days ha^{-1}	
Planting	10 man days ha^{-1}	
Weeding	38 man days ha^{-1}	
Inorganic fertilizer application	4 man days ha^{-1}	
Organic fertilizer application	2 man days ha^{-1}	
Harvesting	24 man days ha^{-1}	
2. Input Costs		
Ammonium Nitrate	USD kg^{-1} N	1.75
P-K-S basal fertilizer	USD kg^{-1} P	3.98
Total seed costs	USD kg^{-1}	2.20
3. Revenue		
Yield	USD t^{-1}	260

Labourer pay rate: USD 3.00

Labour data adapted from Nezomba et al., 2014

Prices are averages for 2011/12 and 2012/2013 cropping seasons for Dendenyore, Wedza, Zimbabwe

NB* Manure price is not included in the Nutrient Expert

6.3 Results

6.3.1 Current farmer management of soil fertility

Farmers showed diverse management practises mainly governed by resource endowment and the field type the farmers were targeting (Table 6.3). Mostly resource endowed farmers could apply basal fertilizers, top dressing and manure. However, the LRE farmers were using woodland litter as an organic amendment due to limited access to cattle manure and mineral fertilizers. Compost was also mainly used by the LRE group as they could afford to put aside their stover for composting, which otherwise would have been used as dry season cattle feed by livestock owners. Across all resource groups farmers showed tactful targeting of nutrients with the poorest fields receiving very little inputs or none at all. Farmers were mainly targeting the good and medium fields. Poor fields in some cases were abandoned or used for legumes such as cow pea. Resource constrained farmers in some instances could not even afford a bag of fertilizer and often had to buy fertiliser re-packaged in 5 kg buckets or 1 kg pockets. This group of farmers often relied on government and other relief organizations for fertilizer hand - outs.

Table 6.3 Common fertility management practices according to resource endowment of farmers in Dendenyore, Hwedza

HRE[1]	MRE[2]	LRE[3]
Manure(>5 t ha^{-1})	Manure (< 5 t ha^{-1})	Woodland litter
Basal fertilizer(>100 kg compound D ha^{-1})	Basal fertilizer (<100 kg compound D ha^{-1})	Top dressing (< 50 kg AN[4])
Top dressing(>100 kg AN ha^{-1})	Top dressing(< 100 kg AN ha^{-1})	Compost (maize stover residues)
		Termitaria soil

[1] HRE High resource endowment [2] MRE Medium resource endowment [3] LRE Low resource endowment [4] AN Ammonium nitrate

6.3.3 Comparison of farmer management practices versus optimised nutrient recommendations using NE

Current farmer management practices were analysed by the NE according to the field type and management practises prevalent in the group. Current management practices reflected the diversity in nutrient management and maize productivity of farms in the various resource groups (Table 6.4).

Table 6.4 Analysis of average productivity across farm typologies in Hwedza, Zimbabwe

Resource endowment	Soil fertility status	Land under maize (ha)	N-P-K applied (kg ha^{-1})	Manure applied (t ha^{-1})	Maize productivity (t ha^{-1})	Total farm production (t)	Net[§] production (t)	Gross margin US\$$farm^{-1}$	Net profit US\$$farm^{-1}$
Low	Low	0.8	20-7-4	0	0.6	0.5	-0.6	68	-213
Medium	Medium	1.4	40-14-7	2	1.5	2.1	1.1	412	-183
High	High	2.1	60-20-10	7	2.0	4.0	2.0	989	645

[§]Net maize production above annual household consumption level

Land under maize cultivation was strongly influenced by resource endowment with the low resource endowment group cultivating areas less than a hectare. The medium to high resource endowment group had land area of 1.4 to 2.1 hectares under maize, respectively as compared to 0.8 hectares for LRE group. Generally farmers' use 70% of their total land for maize as the rest is kept under fallow, or utilised for legumes and other crops. Intensity of fertilizer use increased with increase in farm resource endowment and this translated into higher maize productivity and production for farms with more access to land, fertilizer and manure. The High Resource Endowment group could afford up to 60 kg N ha^{-1} as well as an average of 7 t manure ha^{-1}. The farmers in the LRE category were unable to produce sufficient maize for household requirements under current management, and this is due to a combination of low fertilizer use and poor soil fertility conditions following many years of maize cultivation with little additions of nutrient resources (Table 6.4). Net profit was negative for the MRE and HRE farms. The MRE and HRE farms had excess maize production above household food requirement of 1.1 and 2 t ha^{-1}. Gross profits were positive for all farms, however only HRE farms had a positive net profit of USD 645 when labour costs were taken into account. The results indicate good prospects for maize production intensification under conditions of good soil fertility, large farm size and high investments in fertilizer and manure. The NE suggested application rates of 40 kg N ha^{-1}, 20 kg P ha^{-1} and 10 kg K ha^{-1} for the LRE group to achieve yields of 2 t ha^{-1} (Table 6.5). The advantage of optimised fertilizer management options took into account best crop management practices including weeding and improved plant spacing which were not included in the current management practices; hence the yield and economic benefits are due to a combination of nutrient and agronomic practice

Table 6.5 Optimized fertilizer management strategies across farm typologies in Hwedza, Zimbabwe

Resource endowment	Soil fertility status	Land under maize (ha)	N:P:K application rate (kg ha^{-1})	Maize productivity (t ha^{-1})	Total farm production (t)	Net[§] production (t)	Gross margin (US$ farm^{-1})	Net profit (US$ farm^{-1})
Low	Low	0.8	40-20-10	2.0	1.6	0.4	224	-61
Medium	Medium	1.4	70-30-10	4.0	8.0	6.0	1764	905
High	High	2.1	100-30-10	6.0	12.0	9.0	2760	1560

[§]Net maize production above annual household consumption level

6.3.4 Optimizing fertilizer use for farm typologies addressing drought mitigation

In drought prone areas, nutrient management practices to manage drought risk are important to reduce vulnerability of resource constrained smallholder farmers. Results produced by NE indicated that farmers in Hwedza could manage seasonal droughts by reducing the target yields and the amount of fertilizer applied (Table 6.6). The NE results also showed that during poor rainfall seasons attainable yields were reduced by about 25 - 40%. Reducing the amount of fertilizer, particularly N, applied during soil moisture stress conditions allows farmers in all resource groups to produce sufficient maize to meet household requirements, although the net profits are reduced substantially compared to normal growing seasons. This strategy mostly affects the HRE farms, with changes of attainable yields from 7 down to 4.0 t ha^{-1}. This resulted in a substantial decline in net profits to USD 304 and 100 USD for the HRE and MRE respectively. This offers an important strategy to minimize losses when farmers apply nutrients to target high yields in poor seasons. The strategies to reduce drought risk had small effects on productivity on the MRE and LRE farms, as yields were mostly limited by poor soil fertility conditions.

Table 6.6 Optimising fertilizer use for farm typologies addressing drought situations in Hwedza, Zimbabwe

Resource endowment	Soil fertility status	Land under maize (ha)	N:P:K application rate (kg ha^{-1})	Maize productivity (t ha^{-1})	Total farm production (t $farm^{-1}$)	Net[§] production (t)	Gross margin (US$ $farm^{-1}$)	Net profit (US$ $farm^{-1}$)
Low	Low	0.8	32-20-17	1.5	1.2	0.3	190	-195
Medium	Medium	1.4	40-15-8	2.5	3.5	1.5	642	100
High	High	2	60-25-12	3	6	3	1380	304

[§]Net maize production above annual household consumption level

6.3.5 Optimizing mineral fertilizer use in combination with manure

This scenario applied only to MRE and HRE farms, as the majority of LRE farms in Hwedza had no access to manure. Attainable yields remained unchanged with the application of manure in combination with fertilizer (Table 6.7). However, compared to the optimised fertilizer scenario, application of manure had strong cumulative effects on P and K application resulting in reduced requirements of basal fertilizer, particularly on soils with moderate fertility status. Manure application had no effects on N fertilizer application, mainly due to the low N content (< 1% N) of the manure used by smallholder farmers (Mugwira and Murwira, 1997). Despite the increase in labour for transporting and applying manure, the increased yields and reduced fertilizer costs with manure resulted in a substantial increase in profits for the MRE group.

Table 6.7 Optimizing fertilizer use in combination with manure in Hwedza, Zimbabwe

Resource endowment	Soil fertility status	Land under maize (ha)	N:P:K application rate (kg ha^{-1})	Maize productivity (t ha^{-1})	Total farm production (t)	Net[§] production (t)	Gross margin (US$ $farm^{-1}$)	Net profit (US$ $farm^{-1}$)
Low[1]	Low	0.8	-	-	-	-	-	-
Medium[2]	Medium	1.4	100-18-14	4.0	5.6	3.5	1143	737
High[3]	High	2	120-30-20	7.0	14.0	11.2	3080	1421

[1] No manure applied
[2] 5 t manure use per farm
[3] 10 t manure use per farm
[§] Net maize production above annual household consumption level

6.4 Discussion

6.4.1 Profitability of current fertilizer management practices

Fertilizer management practices are governed by resource endowment. In addition to tailoring recommendations according to nutrient status of soil, cognisance of different farmer groups and nutrient sources available to them must be considered to come up with realistic nutrient recommendations (Carter and Murwira, 1995). Analysis by the Nutrient Expert showed that across all the resource groups returns to fertilizer remain largely suboptimal. Fertilizer use in SSA remains very low with less than10 kg ha^{-1} year^{-1} applied by most farmers (World Bank, 2008). Low fertilizer use across all resource groups remains an obstacle to increased yields. Farmer practices also fail to take cognisance of important issues such as optimal spacing of the maize thereby limiting crop yields. The low resource endowment group had comparably smaller pieces of land than their better resourced counterparts leading to lower productivity. In addition lower fertility status of their fields also severely constrained crop productivity. Generally this group has no access to manure and often use limited amounts of mineral fertilizers. The LRE group remains vulnerable as options to intensify production remain largely out of their reach. With optimal attainable yields of only 2.5 t ha^{-1} their production levels are more suited for subsistence only, thus nutrient recommendations must match their needs.

6.4.2 Blanket recommendations versus site specific recommendations

Background fertility and responses to fertilizer applications are clearly linked as shown in other studies across soil fertility gradients (Mtambanengwe and Mapfumo 2005; Tittonell *et al.,* 2006; Zingore *et al.,* 2007). Fertilizer use efficiencies vary widely across fertility gradients therefore nutrient recommendations that are more targeted and more tailored will greatly improve fertilizer productivity. Analysis of rainfall patterns in Hwedza district show that mid-season droughts are a common occurrence coinciding with maize flowering stage causing decreased yields (Rurinda *et al.,* 2013). Farmers more often than not cite erratic rainfall patterns as a hindrance to using fertilizers (Nandwa *et al.,* 1998). Blanket recommendations are not variable, ignoring the need to vary fertilizer applications according to season quality. This puts farmers at high risk of poor returns to fertilizer investment. The Nutrient Expert system however suggests lower fertilizer application rates and lower target yields when faced with a drought season. Blanket fertilizer recommendations also do not take into account the economics of fertilizer application rates. Thus decision support tools offer ways and means of coming up with economically viable application rates. Generally blanket recommendations are seldom followed as farmers are highly heterogeneous in terms of socio economic backgrounds thus decision support tools like the NE offer farmers recommendations that are more practical.

6.4.3 Practicability of decision support tools in Zimbabwean smallholder farming systems

The practicability of decision support tools (DSTs) in smallholder farming systems will require extensive training of development staff to take them to the farmers. The complexities of smallholder farmers are seldom captured by the DSTs (Matthews and Stevens, 2002) making their effectiveness compromised as smallholder farming systems are diverse. This calls for the use of multiple DSTs to address a particular problem instead of only one (Walker, 2000). Few DSTs have been fully adopted nationwide as the few that were introduced by institutions were only promoted for a particular time period and as soon as the project was over, the use of the

DST was stopped (Struif –Bontkes *et al.,* 2001). The use of decision support tools in Africa has been met with scepticism and poor uptake of the technology as some of the requirements of the DSTs are complex and time consuming. Extension services may also lack the capacity to fully implement such programmes as access to computers and electricity is limited. It should also be noted that DSTs differ in their complexity so the target users must be identified in relation to complexity of information required (Struif -Bontkes and Wopereis, 2003). Some DSTs are better suited for researchers than for extension services. The NE can however be used by extension services as well as research and development personnel (Pampolino, 2012). Challenges of taking computerised technologies to the rural areas remains will remain hindered by information technology literacy. Workshops and outreach programmes will need to be carried out to take this type of technology to the grassroots levels. It should be noted that DSTs are a support for decision making and not a substitute for rigorous decision making (Bouma and Jones, 2001) therefore use of DSTs must be approached with caution.

6.5 Conclusions

The Nutrient Expert has provided analyses on biophysical considerations and resource endowment of farmers when coming up with better agronomic practices. This gives the tool great potential in its usage to streamline fertilizer recommendations in light of heterogeneity prevalent in smallholder farming systems. The LRE group remains the most vulnerable with limited options for intensification. However, the HRE and MRE groups need to increase fertilizer use in conjunction with good agronomic practices for better productivity and increased profitability. Farmer resource endowments define options available to them for soil fertility management as well as land accessible to them. Soil fertility domains are linked to resource endowment. It is important to note that more research and participation from extension and farmers is needed to get the best fertilizer recommendations.

CHAPTER 7

OVERALL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

7.1 Introduction

The main objective of this study was to improve targeting of nutrient resources by smallholder farmers in Zimbabwe. The specific objectives of the study were to: determine N and P use efficiencies under different soil organic carbon levels (Chapter 4); to determine maize yield response to N, P fertilizers when applied with lime or manure on soils with different background organic carbon, (Chapter 5). Chapter 5 also addressed the interactive effects of macro (N, P and K) and micro-nutrient (Zn, Bo, Mn) fertilization and maize productivity on soils differing in organic carbon levels and finally Chapter 6 presented results on the profitability of soil fertility practises across resource endowment groups on smallholder farms. The study presented results of maize yields, nutrient use efficiencies, and water productivity as well as soil chemical changes over two years across three field types as defined by soil organic carbon in central east Zimbabwe. This section summarises the main findings and conclusions of the study. Areas for further research and recommendations for various stakeholders are also highlighted.

7.2 Soil organic carbon as an indicator of soil fertility

The main objective of the study was to improve targeting of nutrients by smallholder farms using SOC as an indicator soil fertility. This was hinged on the hypothesis that SOC can be used to predict nutrient use efficiencies on soils on smallholder farms. The study has shown that SOC is indeed a robust indicator of initial fertility conditions. Results were supportive of the hypothesis as soil fertility domains were defined which can be useful in the development of nutrient recommendations. Maize productivity was lowest in the Field Type 1 (<4 g SOC kg^{-1}soil) category with yields as low as 0.22 t ha^{-1} without added nutrients and maximum yields not exceeding 2.3 t ha^{-1} for the NPKS + manure treatment. This study supports other findings and clearly shows that nutrient use efficiencies are higher on more fertile fields (Vanlauwe *et al.,* 2006; Wopereis *et al.,* 2006). Maize grain yields were significantly higher for soils with >4 g C kg^{-1} soil (Field Types 2 and 3) as compared to Field Type 1, indicating general improved soil fertility status for maize production when SOC > 4 g C kg^{-1} soil. Soil organic carbon below 5 g C kg^{-1} soil can supply less than 50 kg N ha^{-1} and estimations by Carsky and Iwuafor (1995) indicate that such SOC levels can only result in about 1 t ha^{-1} under normal nutrient use efficiencies. It follows then that smallholder farmers must maintain or increase SOC to >4 g C kg^{-1} soil. Smallholder farmers are severely constrained in terms of fertilizer and manure therefore this remains a difficult task to achieve. Studies by Zingore et al. 2007 showed that after 3 seasons of repeated additions of 17 t ha^{-1} SOC increased significantly. Such application rates are virtually impossible in smallholder farming systems. Other studies have noted that total SOC may not be a good indicator of a particular soil function because of the influence of different pools. This therefore means that different proportions of the soluble, particulate, humus and inert pools influence a particular soil function according to their prevalence (Baldock and Skjemstad, 1999). In sandy soils the particulate organic matter plays a greater role in physically binding particles together. The general consensus however is that on soils with < 10 g C kg^{-1} soil there is poor nitrogen supply to plants when there is no added organic matter (Musinguzi *et al.,* 2013). The results from the study are indicative of the prevalence of such soils in communal areas (Chapter 5) therefore additions of manure and litter must be applied to get better yields. There were no significant differences between the NPS and NPKS treatments across the three soil fertility domains, suggesting that the indigenous soil K supply was adequate to support maize production at such yield levels. This is not to say that K must be abolished from current fertilizer formulations as over time nutrient mining will obviously cause a deficiency of K as it will not be replaced in the soil. It is critical for smallholder farmers to appreciate that co-application of N and P is essential for good maize yield responses as yields for NK and PKS treatments were poor across all field types.

7.3 Effect of combining lime or manure with fertilizer on soils with contrasting carbon levels

The second hypothesis for the study was that application of lime or manure significantly influences fertilizer use efficiency on sandy soils. The study showed that manure on smallholder farms despite being of low quality can be used to significantly improve yields on soils >4g C kg soil (field types 2 and 3) in the short term when applied as sole or combined with mineral fertilizer. In the short term however manure has no significant effects on poor soils as yields were not significantly different from the control as a result of immobilization (Ma *et al.,* 1999). Studies have shown that in the long term manure and fertilizer management can rehabilitate degraded fields and bring them back into production by increasing SOC, alleviating micronutrient deficiencies and enhancing soil available N, P and K (Grant 1981.) The build-up of soil organic carbon on sandy soils is however hindered by the low levels of clay and silt that fail to protect organic matter from microbial attacks. In clay soils where clay + silt are high this phenomenon is known as “textural stabilization” and leads to physico-chemical aggregates that sequester organic carbon (Six *et al.,* 2000; Six *et al.,* 2002). Practical application of such methods to farmers who battle to produce food for sustenance from their land is impossible as they would obviously target productive fields instead of investing labour and limited resources on fields which offer little returns. Generally manure in the smallholder farming sector is of poor quality making its sole application ineffective (Mugwira, 1985). Liming did not influence yields on field types 2 and 3 therefore for farmers which such fields liming should not be a priority. However on poor and very acidic soils liming can be a viable option to increase yields as shown by the increase on field type 1 in year 2. The low levels of fertilizer use in southern Africa will remain an impediment to increased crop productivity (Morris *et al.,* 2007).

7.4 Micronutrient additions on sandy soils

The hypothesis that micronutrient additions could improve maize yields was rejected as micronutrient additions had no effect on maize yield responses across all sites. Other studies have however shown that micronutrient additions could improve maize yields on coarse sandy soils as the case in Malawi. (Wendt *et al.,* 1994). In the pre- independence era yields were improved on addition of selected micronutrients in fertilizer blends (Grant, 1981). However yield benefits on addition of fertilizer micronutrients have been surpassed by combinations of manure and fertilizer. As efforts to significantly increase yields in the smallholder sector intensify this will probably lead to less investment in micronutrients by fertilizer companies as macronutrients remain the primary focus. Raising fertilizer usage remains a tall order with SSA having the highest fertilizer costs as compared to the rest of the world.

7.5 Profitability of soil fertility practices across resource endowment groups in Hwedza, Zimbabwe

The profitability of soil fertility practices across resource endowment groups on smallholder farms was the fourth objective and achieved by the use of a Decision Support Tool (the Nutrient Expert). It was a quick way to analyze current fertilizer management practices which proved to be low across all farmer resource groups. However, DST's have often been received with skepticism. Adopting such interventions in the highly heterogeneous farming environments of SSA will assist in improving nutrient use efficiencies as farmers will no longer toil without any idea of associated profitability of their methods. Informed options may soon be accessible to farmers as further research into DST's like the NE are carried out. The Quefts model provided a quick alternative to nutrient omission experiments by generating indigenous N, P and K supply values with good agreement with the nutrient omission experiments. The use of the Quefts model may also assist in coming up with better estimates of indigenous nutrient supply as nutrient omission experiments have a number of shortcomings. These include the fact that when there is a drought underestimation of nutrient supplies will occur due to the poor yields and poor agronomic practises may also lead to poor estimates of indigenous nutrient supplies (Dobermann, 2007).

7.6 Implications of the study for smallholder farmers

The study sought to improve targeting of nutrients by smallholder farmers by defining soil fertility domains and establishing the best niches for application of fertilizers and manure. The study was carried out over only two years and on a total of six sites in the first year and three in the second season. Thus the results need to be taken in that context and not as a panacea to solve smallholder farmers' problems. The soils in the smallholder farming areas are known to be inherently infertile and the study has shown that generally for soils >4 g C kg $^{-1}$ soil there is optimal response to fertilizer additions and manure additions. The degree of implementation of site specific recommendations remains a challenge as recommendations cannot be carried out for each farmer but this study has sought to define soil fertility domains in the broader sense to guide farmers when targeting nutrients. Fertilizer companies obviously cannot produce specific fertilizers for different farmers as this is not practical and would be very expensive. The question would then be, how smallholder farmers can identify such niches? Drawing on previous research by Mtambanengwe and Mapfumo. (2005) there are soil fertility indicators such as colour, texture, management history, termitaria and dominant weed species that can guide farmers to the more fertile niches. The darker the soil, the more soil organic matter and the more clay a soil contains the greater the soil fertility as well as previous applications of organic amendments and fertilizers also make a soil more fertile. Different studies have suggested how smallholders can best tackle heterogeneity. Others have advocated creating uniform niches by building up soil fertility to eliminate gradients (Mtambanengwe and Mapfumo, 2005) or just targeting resources to the more fertile niches as this gave greatest aggregate yields at farm level. (Rowe *et al.,* 2006). Decisions on how and where farmers should target their resources will continue to be determined by other factors as well such as socio – economic status and the type of crop. There are no "one size fits all" solutions to the complexities of the smallholder farming systems.

7.7 Conclusions

Soil organic carbon can be used as an indicator of soil fertility status. A minimum threshold of >4 g C kg^{-1} soil is required to elicit good responses to fertilizer additions. Farmers must target the fertile fields with soil organic carbon > 4 g C kg^{-1} soil so they can better returns to their fertilizer. Farmers who have fields in the field type 1 (≤ 4 g C kg^{-1} soil) must build up soil organic carbon to > 4 g C kg^{-1} soil by application of manure and fertilizers consistently in those fields. Whilst farmers may continue to concentrate organic inputs on already fertile fields this results in diminishing return as this study has shown that in water limited environments there are no discernible differences between field types 2 (>4 -6 g C kg^{-1} soil) and 3 (> 6 g C kg^{-1} soil) . This study confirmed N and P as the overriding limiting nutrients. Current blanket fertilizer recommendations need to be overhauled to address spatial heterogeneity in farms. This is especially so because only considering biophysical factors while ignoring socio-economic status results in non-adoption of recommendations. Balanced nutrient management is needed to improve maize grain and water productivity. Manure remains indispensable in smallholder farming systems for improved use efficiencies.

7.8 Recommendations

Based on findings from this study farmers must strategically concentrate resources on soil with > 4 g C kg^{-1} soil. Farmers need to use balanced fertilization that is N and P to get optimum responses, instead of just applying N alone in the form of ammonium nitrate as commonly practised as this leads to soil degradation. On a national level soil surveys must be taken to verify soils with >4g C kg^{-1} soil to improve targeting of nutrient resources so that fertilizer handouts from the government are targeted on the most productive soils. Cattle schemes and small ruminants may also be introduced to improve access to manure for the majority of smallholder farmers.

7.8.1 Further research

Further research is needed to ascertain the benefits of adding more carbon beyond a certain threshold as the results show that between the thresholds of Field types 2 (> 4− 6 g C kg^{-1} soil) and 3 (> 6 g C kg^{-1} soil) there could be a cut-off for responsiveness to fertilizer. There is therefore need for further research to unravel the fundamentals governing SOC thresholds such as the cut-off point for response to fertilization which are determined by amount of clay.

The scope of this study was limited to one agro-ecological zone. Further research across other ecological zones is needed to come up with options for fertilizer use in other agro-ecological regions of Zimbabwe.

Long term studies to elucidate the impact of cumulative additions of macro and micro nutrients on soil fertility in sandy soils need to be carried out as this study was carried out over only two seasons.

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APPENDICES

Appendix 1 List of publications from this thesis

1. **Natasha Kurwakumire** Regis Chikowo, Florence Mtambanengwe, Paul Mapfumo, Sieglinde Snapp, Adrian Johnston, Shamie Zingore, 2014 *Maize productivity and nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe*. Field Crops Research 164:136-147

2. **Natasha Kurwakumire,** Regis Chikowo, Shamie Zingore, Florence Mtambanengwe, Paul Mapfumo, Sieglinde Snapp, Adrian Johnston, 2015 *Nutrient management strategies on heterogeneously fertile granitic derived soils in Sub-humid Zimbabwe Agronomy Journal* 107: 1-9

3. **Natasha Kurwakumire** Regis Chikowo, Florence Mtambanengwe ,Paul Mapfumo, Adrian Johnston, Shamie Zingore 2012 *Maize yields on heterogeneous light textured soils.* Abstract presented at the Integrated Soil Fertility Management (ISFM) Conference: **"From Microbes to Markets**" Nairobi, Kenya, 22-26 October 2012.

4. **Natasha Kurwakumire** Regis Chikowo, Florence Mtambanengwe, Paul Mapfumo, Adrian Johnston, Shamie Zingore 2013 *Fertilizer management across soil fertility gradients in Zimbabwe.* Abstract presented at the 6th International Nitrogen Conference, Kampala, Uganda, 18-22 November 2013