Feed the crop, not the soil!

Explaining variability in maize yield responses to nutrient applications in smallholder farms of western Kenya

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This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology and Resource Conservation (PE&RC).

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Thesis

Submitted in fulfilment of the requirements for the degree of doctor

at Wageningen University

by the authority of the Rector Magnificus,

Prof. Dr A.P.J. Mol,

in the presence of the

Thesis Committee appointed by the Academic Board

to be defended in public

on Thursday 28 November 2019

at 11:00 a.m. in the Aula.

S Njoroge Kinyanjui

Feed the crop, not the soil! Explaining variability in maize yield responses to nutrient applications in smallholder farms of western Kenya

x + 169 pages

PhD thesis, Wageningen University, Wageningen, The Netherlands (2019).

With references, with summaries in English and Dutch.

ISBN: 978-94-6395-164-7

DOI: https://doi.org/10.18174/503185

Dedicated to the memory of my late father, who had the ability, but lacked the means to pursue higher education, and to my mother, who foresaw the benefit in me furthering my studies, long before it was clear to me.

Crop productivity intensification in smallholder farming systems of sub-Saharan Africa (SSA) is urgently required to improve food self-sufficiency. Increased fertilizer use can address nutrient deficiencies that limit crop productivity in SSA. There is however large uncertainty in crop yield responses to fertilizer applications on farmer fields. This uncertainty has been linked to strong heterogeneity in soil fertility between and within farms. Fertilizer recommendations that account for this spatial heterogeneity are therefore required to better advise farmers, reduce investment and environmental risks for sustainable crop productivity intensification. The main objective of this study was to better understand and explain patterns of maize yield and yield responses to fertilizer applications under heterogenous fertility conditions in smallholder farming systems. This would allow for improved targeting of fertilizer applications, and enable better prediction of expected crop yield response to fertilizer use.

A series of on-farm experiments assessing maize yield response to fertilizer application under variable soil fertility conditions were established on 23 farmers' fields in Siaya, western Kenya across multiple seasons. Prior to experiment establishment, farmers were extensively interviewed to obtain information on past crop and nutrient management practices in selected fields. The experiment used was comprised of nutrient omission trials (NOTs) on farmer fields in Siaya to assess patterns of maize yield response to fertilizer applications of 150 kg ha^{-1} nitrogen (N), 40 kg ha^{-1} phosphorus (P) and 60 kg ha^{-1} potassium (K). In Phase 1, plots with treatments including control, PK, NK, NP and NPK were repeated for 7 consecutive seasons in the same plots. In Phase 2 of the experiment, a second set of NOTs including PK, NK, NP and NPK were established in every plot on 6 fields that were previously part of Phase 1. On 13 other fields from Phase 1, all plots received NPK in Phase 2. Yields and above ground biomass were measured every year, soil samples were taken in 2013, 2014, 2016 and 2018 and plant samples were taken in 2016 and 2018. Spatial-temporal patterns in yield and yield responses were studied and compared with soil and farmer characteristics. Yield response to soil nutrient supply was studied with the QUEFTS model, and the RC-P model was used to study fate of fertilizer P. Nutrient balances were calculated.

The frequency and magnitude of maize yield response to fertilizer N, P and K varied strongly over space and time, yet observed patterns were not adequately explained by soil chemical parameters or texture. Fertilizing with N, P, and K substantially reduced observed spatial-temporal variability in maize yield response, and resulted in consistently enhanced maize yields. All fields were responsive to N, most fields to P and only 7 to K. On average, NPK yields were about 5 to 5.5 tons ha^{-1} in the short- and

long rainy seasons respectively. Application of only NP or NK resulted in strongly declining yields within a few seasons, with large differences between farms in resilience of soil P and K stocks. Based on observed spatial-temporal patterns, we concluded that blanket fertilizer recommendations in such farming systems result in low fertilizer use efficiencies. We further concluded that current methods for soil analysis do not adequately explain the observed variation in maize yield response to application of N, P and K fertilizers under the highly variable soil fertility conditions encountered in smallholder farming systems.

Accounting for past manure application in Phase 1 of the experiment improved our ability to explain the variation in maize yield response to fertilizer application. Mean maize yield response to N, P and K application was 2.8, 1.1 and 0.6 t ha^{-1} in fields with animal manure previously applied, and 2.3, 3.0 and 1.6 t ha^{-1} in farms without past manure applications over 7 cropping seasons. Differences in maize yield response in fields with and without past manure applications were mainly related to enhanced soil phosphorus (P) and potassium (K) supply, and larger recovery of applied nitrogen (N) in fields with manure previously applied. Based on these findings, we concluded that the strong influence of past animal manure application on yield response to fertilizer applications merits the inclusion of past manure application as a co-variate in analysis of yield response data from smallholder cropping systems of SSA.

The Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model did not adequately estimate crop yield responses to fertilizer applications under variable soil fertility conditions. This was linked to poor estimation of soil N, P and K supply based on current relationships for potential soil nutrient supply in the QUEFTS model. In particular, soil organic carbon (SOC) and P-Olsen were poor indicators of crop N and P uptake from the soil. Maize grain yield in unfertilized control treatment plots provided better estimates of potential soil N, P and K supply, resulting in improved predictions of maize yield response to fertilizer applications. These findings suggest that the standard soil parameters analysed do not accurately inform on the soil fertility status of the field and are of little use for smallholder farmers. Improved relations for estimation of potential soil nutrient in QUEFTS are required for better prediction of expected maize yield response to fertilizer application under variable soil fertility conditions.

Maize crops in strongly nutrient-depleted soils responded strongly to balanced NPK fertilization, with yields comparative to long-term means within three seasons. Placement of P fertilizer strongly improved recovery, reducing the need for larger soil P stocks on soils that will typically develop a large insoluble P pool under P fertilization. The RC-P model provided insights in long-term recovery of P and could describe the observed P uptake patterns reasonably well. We concluded that strongly nutrient depleted tropical soils such as those in Siaya with high clay contents that are typical for western Kenya, do not require prior investments to rebuild nutrient stocks and soil organic matter to substantially increase crop yields to 5-5.5 t ha^{-1}. This has important implications for crop productivity intensification in SSA as a large proportion of soils under cultivation are strongly nutrient depleted, and earlier approaches have suggested the need for costly and capital intensive soil fertility replenishment.

Results in this thesis clearly demonstrate that sustainable intensification of crop productivity on smallholder farms of SSA is very well possible on all fields under good management, even when soils are strongly nutrient depleted. However, the need for P and K fertilizers and amounts applied should be tailored to specific field conditions to reduce farmer costs in the short term. Accounting for past farm management and assessment of current yields under minimal or no fertilizer applications provides a means for improved targeting of fertilizer applications at the farm level. In the long term, farmers should aim for balanced fertilization to prevent mining of soil stocks. Simplified decision support tools that use field level information to develop improved estimates of fertilizer N, P and K requirements based on refined relationships between soil nutrient supply, nutrient uptake and yield, are required to derive fertilizer recommendations in future.

Contents

Chapter 1

General introduction

1.1 Background

Food insecurity remains a global concern with up to 10% of the world's population currently food insecure (FAO, 2018b). In sub-Saharan Africa (SSA), food insecurity is a bigger concern with close to 30% of the population in SSA currently food insecure (FAO, 2018b). Future projections paint an even grimmer picture with the projected 2.5 fold increase in population by the year 2050 expected to result in a tripling in demand for cereals (Van Ittersum *et al.*, 2016), the key staple foods. This illustrates the vast challenge of ending global hunger and malnutrition, and attaining food security by 2030 as set out by the United Nations General Assembly (UN, 2015), particularly in SSA. As crop production serves as the key driver of food availability in SSA (Frelat *et al.*, 2016), significant improvements in current and future food security will largely be based on crop productivity intensification.

Crop production in SSA mainly occurs under rainfed permanent cropping (Binswanger-Mkhize, 2017) in smallholder farming systems characterised by small farm sizes (Deininger *et al.*, 2017). Crop productivity in these farming systems is however low due to poor soil fertility as a result of continuous cropping with little or no nutrient replenishment (Sanchez, 2002). Subsequently, actual yields of cereals in these smallholder farming systems are very low compared to attainable yield (GYGA, 2019), resulting in large yield gaps. For example, actual rainfed yields of maize the most important cereal crop in SSA (Shiferaw *et al.*, 2011) during the period 2003 – 2012 ranged from 1.2 to 2.2 t ha^{-1}, representing only 15 – 27% of the water-limited yield potential (i.e. the attainable yield under optimum management under rainfed conditions) (Van Ittersum *et al.*, 2016; Van Ittersum and Cassman, 2013). Such large differences in actual versus attainable yields result in low cereal self-sufficiency ratios within countries in SSA, prompting substantial reliance on food imports to meet food demand (Van Ittersum *et al.*, 2016). Despite current low crop productivity, SSA has a large potential to intensify production and significantly close current yield gaps of major cereals. For exmple, addressing of nutrient deficiencies alone would help to close maize yield gaps to 50% of attainable yields (Mueller *et al.*, 2012). Improved fertilizer use within smallholder farming systems of SSA is a key pathway for addressing nutrient deficiencies, and sustainably intensifying crop productivity.

1.2 The role of fertilizers in crop productivity intensification

Fertilizers are the key source of external nutrient supply under continuous cultivation (Dobermann, 2007; Reetz, 2016). Fertilizers are primarily produced from naturally occurring nutrient deposits and the industrial fixation of atmospheric nitrogen (N) (Chianu and Mairura, 2012). Compared to other external nutrient sources such as organic residues and animal manure, fertilizers contain larger concentrations of nutrients in a form more available to crops and are easier to apply (Chianu and Mairura, 2012). Fertilizers amend soil fertility, maintain and increase crop productivity and help to sustain the capacity of soils for future crop production (Chianu and Mairura, 2012; Reetz, 2016). Globally, mineral fertilizers have sustained agriculture for more than 100 years (Smill and Streatfeild, 2002; Stewart *et al.*, 2005), with up to 50% of global crop yields attributable to fertilizer use (Stewart *et al.*, 2005). The contribution of fertilizers to increasing crop yields has been credited with sparing millions of hectares of natural ecosystems that would otherwise have been converted to agriculture to meet the planet's growing food needs (Balmford *et al.*, 2005). Inappropriate, imbalanced, limited or excessive use of fertilizers in agricultural systems however remain a concern. Nutrient mining is common when limited amounts of fertilizers are applied (Dobermann, 2007; Ryan, 2007) as is often the case in SSA, while losses of applied nutrients to the environment are likely following excessive or improper applications of fertilizers (Van Noordwijk and Cadisch, 2002; Krauss, 2007). Sustainable fertilizer use should therefore be based on balanced fertilization, and proper application of fertilizers. Balanced fertilization refers to the proper supply of all essential crop nutrients in a balanced ratio throughout the growth of crops (Cisse, 2007). Fertilizer recommendations that take into account crop nutrient uptake requirements, nutrients limiting crop productivity and additional sources of nutrients are essential for ensuring balanced fertilization (Cisse, 2007). Proper application of recommended quantities of fertilizer in synchrony with plant uptake patterns (Buresh and Witt, 2007; Reetz, 2016) and right crop agronomic practices are also essential for efficient use of fertilizers for crop productivity intensification.

1.2.1 Fertilizer use in smallholder cropping systems of sub-Saharan Africa

Fertilizer use in smallholder cropping systems of SSA has been characterised by low mean annual application rates (Sattari *et al.*, 2012; Minot and Benson, 2009) below those required for optimum crop production and maintenance of soil fertility. Resulting nutrient limitations following soil fertility depletion have been identified as the principal cause of the large gap between potential and actual crop yields on smallholder farms (Tittonell *et al.*, 2005a; Adediran and Banjoko, 1995). Subsequently, increased fertilizer use was identified as the key avenue for raising crop productivity in smallholder systems of SSA (Africa Fertilizer Summit, 2006). This led to the revival of large-scale fertilizer subsidy programs in a growing number of SSA countries (Jayne *et al.*, 2018), resulting in increasing fertilizer application rates (Sheahan and Barrett, 2017), compared to a mean value of 13 kg ha^{-1} reported a decade ago (Minot and Benson, 2009). The increase in fertilizer use has however not translated into substantial increases in crop productivity, with mean yields of important crops still low (FAO, 2018a). This has been related to substantially lower mean crop yield responses on smallholder farms compared to large responses often observed on research stations (Jayne *et al.*, 2018) where most fertilizer recommendations are developed. Low mean crop yield responses to fertilizer applications result from large and unpredictable variations in crop yield response to fertilizer application between and within farms (Burke *et al.*, 2017; Kihara *et al.*, 2016; Vanlauwe *et al.*, 2006). Such variations negatively affect strategies aimed at crop productivity intensification based on increased fertilizer use, as farmers are hesitant to adopt higher fertilizer application rates when benefits are perceived to be low and/or uncertain (Marenya and Barrett, 2009; Xu *et al.*, 2009). Crop productivity intensification on existing farms based on increased fertilizer use to address nutrient deficiencies is therefore still elusive, and food security in SSA remains a concern. Improved understanding of patterns and drivers of crop yield variations to fertilizer use within smallholder farming systems is required for sustainable crop productivity intensification based on increased fertilizer use.

1.2.2 Variations in crop yield response to fertilizer applications

Variations in crop yield responses to fertilizer applications between and within farms have been attributed to the spatial heterogeneity of many smallholder farms in terms of soil quality (Tittonell *et al.*, 2008b; Giller *et al.*, 2011). At the regional level, differences in soil quality are related to differences in geomorphology, local climate and vegetation (Deckers, 2002; Smaling *et al.*, 1993). Between farms, differences in access to nutrient resources result in strong differences in soil fertility over time (Giller *et al.*, 2006; Tittonell *et al.*, 2005b). Within farms, inadequate quantities of fertilizer and manure resources often lead to preferential allocation of nutrients to fields close to the homestead resulting in strong differences in soil fertility based on distance from the homestead (Zingore *et al.*, 2007a; Tittonell *et al.*, 2005b). Initial differences in soil quality within farms are also further reinforced following farmers' prioritization of crop and soil management in fields within their farms perceived to be more fertile (Tittonell *et al.*, 2008b).

Observed strong differences in soil quality between and within smallholder farms in SSA imply the need for fertilizer recommendations that account for the spatial heterogeneity in these farms. Current fertilizer use recommendations in most of SSA fail to account for this heterogeneity. For example, in Kenya fertilizer recommendations for maize production are based on regional soil surveys based on administrative boundaries (NAAIAP, 2014). In Zimbabwe, fertilizer recommendations are linked to agro-ecological zones that are principally delineated based on rainfall, despite large variability in soils over short distances (Zingore *et al.*, 2007a). On-farm studies in western Kenya and eastern Zimbabwe have however demonstrated the strong influence of differences in soil quality on maize yield response to fertilizer N, P and K applications (Vanlauwe *et al.*, 2006; Kurwakumire *et al.*, 2014). By untangling such yield response patterns, it is possible to develop more targeted fertilizer recommendation practices, resulting in enhanced crop productivity in the face of heterogeneity in soil quality. For example Giller *et al.* (2011) showed that the broad heterogeneity of fields in SSA can be summarised into three categories (i.e. fertile non-responsive fields, responsive fields, and infertile non-responsive fields), with distinct fertilizer recommendation practices required to maintain and/or restore the productivity of fields in each of the categories. This indicates that detailed understanding of the magnitude and frequency of yield response patterns to fertilizer applications over space and time can help to substantially fine-tune current fertilizer recommendation to account for spatial heterogeneity.

1.3 Study rationale and objectives

Large variations in crop yields' response to fertilizer applications on smallholder farms of SSA limit crop productivity intensification efforts based on increased fertilizer use. Improved fertilizer use recommendations that account for the strong spatial heterogeneity in smallholder farming systems of SSA are necessary if substantial improvements in crop productivity based on increased fertilizer use are to be achieved. Earlier studies have quantified the magnitude of crop yield responses to fertilizer applications in smallholder farms of SSA (Vanlauwe *et al.*, 2006; Wopereis *et al.*, 2006; Zingore *et al.*, 2007b), and developed proposals for fertilizer management based on observed soil response categories (Giller *et al.*, 2011). However, given that soil quality is a dynamic function, it is expected that initially observed response patterns will change over time based on nutrient management practices imposed and cropping intensity. For example, soils initially observed to be fertile non-responsive may over time require larger fertilizer applications beyond those required for maintenance of soil fertility due to declining soil nutrient stocks. There is therefore need to additionally account for expected changes in yield response patterns over time, if improved fertilizer recommendations are to be sustainable. Information on such response patterns is however lacking. Further, there is limited information on the specific contribution of soil and management factors on crop yield response to fertilizer application at the field level. Multiple season on-farm studies evaluating changes in crop yield and soil nutrient stocks following varied nutrient application regimes on heterogeneous farms offer the most straightforward way of quantifying spatial-temporal variations in yield responses and soil quality. Comparison of observed patterns with predictions from simulation models also offers an opportunity to further improve on model predictions, allowing for more refined predictions of expected long-term patterns. In light of this, this study mainly aimed at providing a detailed quantification and explanation of the magnitude and spatial-temporal patterns of crop yield responses to nitrogen (N), phosphorus (P) and potassium (K) applications in heterogeneous farms varying in soil quality. Specific objectives were to:

i. Assess the variability, magnitude and spatial-temporal patterns of maize yield responses to N, P and K application in smallholder fields in an intensively farmed area of western Kenya *(Chapter 2)*.
ii. Identify and quantify the specific contribution of the key soil and management factors causing variability in maize yield response to fertilizer N, P and K application *(Chapter 3)*.
iii. Evaluate the ability of simplified decision support tools to predict expected maize yield response to fertilizer application under highly variable field conditions *(Chapter 4)*.
iv. Assess patterns of changes in crop productivity and soil nutrient stocks following balanced fertilizer application on soils with imbalanced and depleted soil nutrient stocks *(Chapter 5)*.

1.4 Study area and research methodology

This study was conducted in Siaya county in the highlands of western Kenya. The highlands of western Kenya support one of the densest rural populations in SSA (Jayne and Muyanga, 2012; Vanlauwe *et al.*, 2006). Crop production takes place on small farms (Jayne and Muyanga, 2012), and mainly involves cultivation of maize (*Zea mays* L.), the key staple crop in western Kenya (Place *et al.*, 2006). Agroecological potential for crop production is high due to a bimodal rainfall regime and relatively deep soils dominated by clay and loam textures (Tittonell *et al.*, 2008b). Continuous cropping with minimal or no nutrient inputs has however led to strong nutrient depletion (Soule and Shepherd, 2000; Shepherd *et al.*, 1995), resulting in widespread poor soil fertility (Tittonell *et al.*, 2005b). Subsequently, despite water limited yields of 12 t ha^{-1} and 8 t ha^{-1} in the long and short rainy seasons respectively, actual maize yields on majority of smallholder farms in western Kenya are low at about 1.9 t ha^{-1} (GYGA, 2019). This has resulted in large yield gaps, and low maize self-sufficiency (Tittonell *et al.*, 2005a). The western Kenya region is also characterized by large within and between farm heterogeneity in soil fertility (Tittonell *et al.*, 2005b). This region is broadly representative of other east African highlands with comparable soil types, climate and demography (Braun *et al.*, 1997), presenting the scope for applicability of findings over large areas.

The study used a combination of multi-locational on-farm experiments conducted in three phases over eleven consecutive cropping seasons. Phase 1 of the experiment comprised of nutrient omission trials established on 23 different farmers' fields with no replication. This experiment ran for seven consecutive seasons (long rainy season of 2013 to long rainy season of 2016). Phase 2 of the experiment was established after the end of Phase 1, and included 17 farms previously under Phase 1 after 6 farms dropped from the study. Phase 2 included two sets of experiments namely Phase 2-NPK, and Phase 2-NOT. In Phase 2-NPK, balanced NPK experiments were established on 13 farms previously under nutrient omission trials in Phase 1. In Phase 2-NOT, superimposed nutrient omission experiments were established on the remaining 4 farms. Experiments in Phase 2 ran for four consecutive seasons (short rainy season of 2016 to long rainy season of 2018).

1.5 Thesis outline

This thesis is composed of six chapters. This chapter presents the general background to the study of problems facing crop production in smallholder farming systems of SSA, and the potential role of fertilizer use in intensifying crop productivity in these farming systems. Chapter 2 uses maize yield data from Phase 1 of the experiment to assess and quantify spatial-temporal patterns of maize yield response to fertilizer applications. Chapter 3 uses maize yield, nutrient uptake, soil analysis and socio-economic data from experiments in Phase 1 to identify and quantify the key field level factors driving variability in maize yield response to fertilizer applications. In Chapter 4, maize yield, nutrient uptake and soil analysis data from the last season of Phase 1 is used to assess the accuracy of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model in predicting maize yield response to balanced and imbalanced fertilizer application under highly variable farm conditions. Chapter 5 uses data from experiments in Phase 2 to assess patterns of changes in crop productivity and soil nutrient stocks following balanced fertilizer application on soils with imbalanced and depleted soil nutrients. In Chapter 6, findings from Chapters 2 – 5 are integrated to develop insights for sustainable maize productivity intensification on smallholder farms of SSA based on enhanced fertilizer use.

Chapter 2

Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms

This chapter is published as:

Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. Field Crops Research 214, 321-330.

Abstract

Large variability in crop responses to macronutrient application at various spatial scales present challenges for developing effective fertilizer recommendations for crop production in smallholder farming systems of sub-Saharan Africa. We assessed maize yield responses to nitrogen (N), phosphorus (P) and potassium (K) application and evaluated relationships between crop responses to N, P and K application and soil analysis data. Nutrient omission trials were conducted on 23 farms located in Sidindi, western Kenya, selected to be representative of the main soil and management factors in maize based systems in Siaya County. Treatments included a control and PK, NK, NP and NPK applications. The trials ran for six consecutive cropping seasons, without changing treatments or plot location, covering the period 2013–2015. Strong spatial-temporal patterns in maize yield responses to N, P and K applications were observed. Average maize yields in the control, PK, NK, NP and NPK treatments were 2.8, 3.2, 5.1, 5.1 and 5.5 t ha^{-1} at 88% dry matter respectively in the first cropping season, and 1.1, 1.4, 2.9, 3.6 and 5.3 t ha^{-1} at 88% dry matter respectively in the sixth cropping season. In all seasons, variability in maize yield between fields was greatest in the control treatment followed by the NK treatment and least in the NPK treatment. Mean relative yield was 0.6, 0.92 and 0.93 for N, P and K respectively, in the first cropping season, and 0.25, 0.52 and 0.68, respectively, in the sixth cropping season. Six main maize yield response categories were identified that differed in observed maize grain yield responses to recursive N, P and K applications. Maize yield responses to N, P and K were not fully accounted for by soil organic matter, soil available P and exchangeable K respectively. Our results indicate that current methods for soil analysis do not adequately predict the response to application of N, P and K fertilizer under the highly variable soil fertility conditions encountered in smallholder farming systems. The strong spatial-temporal patterns observed present major challenges for the development of effective site-specific fertilizer recommendations. Potential avenues for future research and options for more effective intensification strategies are discussed.

Key words: Soil fertility variability, nutrient omission trials, relative yield, sub-Saharan Africa

2.1 Introduction

Crop production in smallholder systems in sub-Saharan Africa (SSA) is strongly limited by poor soil fertility that results from continuous cropping with little or no nutrient replenishment (Kihara *et al.*, 2015; Sanchez, 2002), with an average fertilizer application rate of 13 kg ha^{-1} (Minot and Benson, 2009). Soil deficiencies of macronutrients are widespread in the region, with negative nutrient balances reported for nitrogen (N), phosphorus (P) and potassium (K) in most parts of SSA (Xu *et al.*, 2014). As a result, the yields obtained by farmers using local practices of important food crops in the majority of smallholder farming systems in SSA are far below the attainable yield (Van Ittersum *et al.*, 2016) resulting in yield gaps, defined as difference between actual and potential yields under rainfed conditions without nutrient deficiency, pest or diseases (Van Ittersum and Rabbinge, 1997). In the last decade for SSA, actual rainfed maize yields ranged from 1.2 to 2.2 t ha^{-1}, representing only 15-27% of the potential yield under rainfed conditions (Van Ittersum *et al.*, 2016). Consequently, SSA has been identified as one of the regions in the world with the lowest cereal sufficiency ratio defined as the ratio between domestic production and total consumption (Van Ittersum *et al.*, 2016).

Given that up to 75% of the population in SSA depend directly or indirectly on agriculture as a livelihood source (Sanchez *et al.*, 2007; Nziguheba *et al.*, 2010), the sector’s large contribution to the overall economy (Diao *et al.*, 2010), and the projected decrease in cereal self-sufficiency over time (Van Ittersum *et al.*, 2016), agricultural intensification is urgently needed (Tittonell and Giller, 2013). Considerable ‘low hanging’ opportunities exist for intensification of production of major cereals in SSA (Mueller *et al.*, 2012) when N, P and K deficiencies are addressed (Adediran and Banjoko, 1995). Since the launch of the Alliance for Green Revolution in African (AGRA) in 2006 (AGRA, 2017), and the recommendations of the Africa fertilizer summit of 2006 (Africa Fertilizer Summit, 2006), a number of research programmes have focused on intensification of crop productivity in smallholder farming systems in SSA (Chikowo *et al.*, 2014). Although fertilizer use has increased in a number of countries in SSA, its use efficiency remains low due to poor crop management practices (Byerlee *et al.*, 2007; Sheahan and Barrett, 2014), the predominance of inherently low fertility sandy soils (Bationo *et al.*, 2012a), and unbalanced blanket fertilizer recommendations that do not address the complexity of smallholder farming systems (Giller *et al.*, 2011; Chikowo *et al.*, 2014). Further, the occurrence of “non-responsive soils” where application of available fertilizers does not result in increased crop productivity (Vanlauwe *et al.*, 2010) has an additional adverse effect on fertilizer use efficiency. Such non-responsiveness may be due to a range of factors including macro- and micronutrient depletion, poor germination due to slaking or top-soil erosion, aluminium toxicity in relation to soil acidification and increased sensitivity to drought conditions (Vanlauwe *et al.*, 2015; Tittonell and Giller, 2013). As a result, crop productivity intensification programmes in SSA have faced large variations in yield responses to applied nutrients at farm and field scales (Tittonell *et al.*, 2008b; Vanlauwe *et al.*, 2006). This raises the need for fertilizer recommendations that are tailored for specific farm and field conditions (Smaling *et al.*, 1992; Tittonell *et al.*, 2008a). Although, inherent soil fertility is related to soil forming factors including geomorphology, local climate and vegetation (Deckers, 2002; Smaling *et al.*, 1993), cropping intensity and past soil management have been identified as major drivers of variability (Tittonell *et al.*, 2005b). The centripetal net transport of nutrients by animals also results in strong gradients at landscape level (Van Keulen and Breman, 1990). The strong effects of management often result in patterns of decreasing soil fertility with increasing distance from homesteads within farms (Zingore *et al.*, 2007a; Tittonell *et al.*, 2005b) and decreasing soil fertility with decreasing resource availability and use among farms (Giller *et al.*, 2006; Tittonell *et al.*, 2005b). Consequently, regions and or farms with similar inherent soil fertility may over time develop strong heterogeneity in soil fertility and associated responses to macronutrients (N, P and K) applications. There is a paucity of information on both spatial and temporal patterns of such responses. Spatial-temporal patterns refer to differences in the dynamics of crop yield responses to macronutrients applications in an area with similar climatic conditions. This is because most nutrient management technologies were developed at research stations without sufficiently acknowledging the complexity of farming systems (Chikowo *et al.*, 2014). Such information would help to target the right fertilizer and application rates to specific crops and locations and improve the efficiency of fertilizer use (Kihara *et al.*, 2016). Further, understanding the relationships between spatial-temporal responses to macronutrients application and soil analysis results would help in quantifying the value of soil analysis, which is considered an important component of restoring and managing soil fertility in smallholder farming systems (Sanginga and Woomer, 2009). Controlled experiments in a series of heterogeneous farmers' fields therefore offer the most conceptually straight forward way to study spatial temporal variations in responses to macronutrients (Lobell *et al.*, 2009; Vanlauwe *et al.*, 2006). Further insight on the magnitude, and consistency of observed spatial temporal patterns over time can then be achieved using cluster analysis (Perez-Quezeda *et al.*, 2003). Cluster analysis allows for the grouping of fields showing similar responses over time into distinct classes (Fridgen *et al.*, 2004), and was used effectively to identify various classes of nutrient response patterns in smallholder farming systems in SSA (Kihara *et al.*, 2016).

The specific objectives of this study were to: (i) assess the magnitude and spatial-temporal patterns of maize yield responses to N, P and K application; (ii) identify and characterize clusters of farms with similar yield response patterns to N, P and K; (iii) assess the utility of soil chemical properties in predicting maize responses to N, P and K application. We hypothesize that patterns of crop responses to N, P and K fertilization over a combination of space and time in heterogeneous farms provide an important basis for developing site-specific fertilizer recommendations.

2.2 Materials and methods

2.2.1 Study site

The study was conducted in Sidindi, western Kenya. A 10 km by 10 km site previously used to collect soil mapping data under the African Soil Information Services (AfSIS) project (http://africasoils.net) was selected. The site is centred at a latitude of 0.15 ^{o}N, a longitude of 34.4^{o}E and at about 1240 metres above sea level. Annual rainfall ranges from 1600 – 2000 mm and is distributed over two distinct seasons with a long rains (LR) season from March to July and short rains (SR) season from September to December. Maize is the main staple food crop and is cultivated on more than 80% of the crop area in western Kenya (Place *et al.*, 2006). Despite water limited yields (Yw) which refers to the yield achievable in farmer's fields with best nutrient, pest, and crop management practices under rainfed conditions (Van Ittersum *et al.*, 2013) of 12 t ha^{-1} and 8 t ha^{-1} in the long and short rains seasons respectively, actual maize yields on majority of smallholder farms in western Kenya are low at about 1.9 t ha^{-1} (Van Ittersum *et al.*, 2016). The area is also characterized by large within and between farm heterogeneity in soil fertility (Tittonell *et al.*, 2005b).

2.2.2 Selection of trial sites

On-farm nutrient omission trials were established in 2013 across 24 sites representative of major soil units in the study area. Selection of trial sites was conducted on the basis of a previous survey conducted by the AfSIS project (http://africasoils.net) that collected socio economic and agronomic data from 300 farmers within the study site (data not shown). From this survey, stratified random sampling was conducted to select an initial sample containing 48 farms representative of the study area based on land size, socio-economic characteristics and soil type.

From this sample, eight fields within each of the three sub-locations in the study area namely Sirembe, Malanga, and Ndere were selected based on the availability of land for trial set-up to make a total of 24 fields. Seasonal rainfall data in each of the sub-locations was collected using rain gauges located at each of the sub-locations. The experiments were conducted for six consecutive cropping seasons in 2013 – 2015.

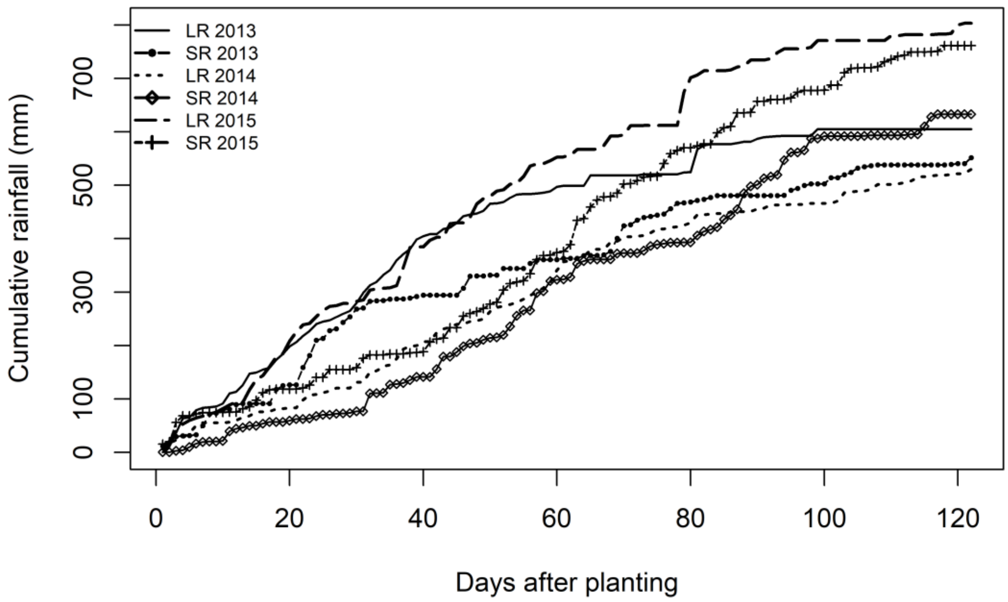

Fig. 2.1: Cumulative average rainfall in the long rainy (LR) and short rainy (SR) seasons of 2013 - 2015.

2.2.3 Site characterization

Prior to the establishment of the trials, the position of each field was determined using a Global Navigation Satellite Systems receiver (Etrex 20, Garmin Limited, Chicago USA). Soil samples were collected from four points within each field using a ‘Y frame sampling approach’ at a 0-20 cm depth. Collected samples were then placed in a basin, thoroughly mixed and a composite sample obtained. Composite samples from each field were then air dried and passed through a 2 mm sieve before chemical analysis at Crop Nutrition Laboratories in Nairobi. Available P and exchangeable bases (calcium, magnesium, K and sodium) were determined after a Mehlich 3 extraction (Mehlich, 1984), while soil organic matter (SOM) was determined using the Walkley-Black method (Robinson, 1993). Soil pH was determined in water, while soil texture was determined using the hydrometer method after adding a dispersing solution to a 50 g sample of soil (Bouyoucos, 1962).

2.2.4 Experimental treatments and management

The first set of nutrient omission experiments was established in early April 2013 at the onset of the long rainy season. The experiment included a set of five treatments to assess maize response to N, P and K application including a control, P+K, N+K, N+P and N+P+K treatments established in plots measuring 10 m by 10 m (Table 2.1) replicated in 24 farms with each farm serving as a complete block. N was applied in the form of urea in three equal splits; at planting, at three weeks after emergence and at six weeks after emergence. The P and K fertilizers were applied at planting in the form of triple super phosphate (TSP) and muriate of potash (KCl) respectively. Trial plot locations and allocated treatments remained the same throughout the study period.

Each season, fields were prepared about two weeks before seeding by tilling to a depth of approximately 20 cm using hand hoes. Remaining crop residues from the previous season were removed prior to tilling, reflecting normal farmer practice. Throughout the experimental period, the short-season maize variety DK8031 was planted at the recommended spacing (75 by 25 cm) to give 53,333 plants ha^{-1} after thinning. Two seeds were planted per planting station and thinned to one at two weeks after emergence. All plots were manually weeded at three and six weeks after emergence.

Table 2.1: Treatment structure for nutrient omission trials in Sidindi, western Kenya.

Treatment	Nutrient		
	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Control	0	0	0
PK	0	40	60
NK	150	0	60
NP	150	40	0
NPK	150	40	60

2.2.5 Yield data collection

At physiological maturity, all maize plants were harvested within a net plot of 2.25 m by 3 m including three centre rows in each plot, leaving at least 2 m on each side of the centre rows to minimize edge effects. The exact location of the net plot was chosen such that the net plot was visually representative of general growth conditions within the centre rows. After harvesting, total plant and cob numbers were recorded, and total cob weight determined in the field using a digital scale accurate to 2 decimal places. Grain moisture content was determined using a moisture tester (Dickey John Mini GAC, Minneapolis USA). Grain yield in each plot was then expressed in 88% dry matter.

2.2.6 Relative yield

Relative yield (RY) was used as a measure of the yield responses to N, P and K and was determined as the ratio between nutrient limited yield and yield in the NPK plot (equation 1). Relative yield values <1 indicate response to the applied nutrient, while values >=1 indicate no response to the applied nutrient.

$$RY_{i,j,s} = \frac{GY_{i,j,s}}{GY_{npk,j,s}} \tag{1}$$

Where;

$RY_{i,j,s}$ = Relative yield in treatment plot *i* at field *j* in season *s*

$GY_{i,j,s}$ = Grain yield in treatment plot *i* at field *j* in season *s*

$GY_{npk,j,s}$ = Grain yield in the NPK treatment plot at field *j* in season *s*

2.2.7 Normalized yield

Yield normalization was conducted to enable comparisons of plot performance with other plots that received the same treatment in the same season, i.e. highlighting spatial differences. It allows evaluation of the resilience of plot nutrient stocks over time. It also allows evaluation of changes in ranking of plots over time, enabling understanding of key factors that may identify better performing plots. Normalized yield (NY) was determined as the ratio between the yield for a particular treatment and season in a particular field and average treatment yield for that treatment across all fields in a particular season (Equation 2). When normalized yields are trending downwards, this reflects a smaller resilience when compared to other plots and when trending upwards it reflects a larger resilience, both indications of changing spatial patterns.

$$NY_{i,j,s} = \frac{GY_{i,j,s}}{\overline{GY_{\iota,s}}} \quad (2)$$

Where;

$NY_{i,j,s}$ = Normalized yield in treatment plot *i* at field *j* in season *s*

$GY_{i,j,s}$ = Grain yield in treatment plot *i* at field *j* in season *s*

$\overline{GY_{\iota,J,s}}$ = Overall mean grain yield in treatment plot *i* across all fields in season *s*

2.2.8 Statistical analysis

The final dataset used in the analysis comprised of data from 23 fields after one field was excluded due to lack of yield data in the fifth and sixth season following farmer withdrawal from the study. The effect of treatment on grain yield in the 23 fields was analysed at seasonal level using a generalised linear model with grain yield as response variable and treatment as explanatory factor with the LME4 package available in R software (R Core Team, 2017). Differences in treatment means were then evaluated for significance using a Tukey HSD test with the package 'agricolae' in R and reported at a significance level of 0.05. To evaluate the differences in yield variation between and within treatments, the coefficient of variation (CV) was calculated for each treatment in each season (using the 'raster' package in R). Scatter plots of CV values and seasons were then constructed and regression lines fit for trend assessment.

To assess differences in response to N, P and K, a Student t-test was used to evaluate if seasonal relative yield values were different from a value of 1.0. Evaluation of differences in response to N, P and K over time was conducted using a GLM model with treatment relative yield as response variable and season as explanatory factor. Frequency distribution plots were then used to show trends in relative yield at field level over seasons.

Cluster analysis was used to identify groups of fields with similar trends in yield responses to N, P and K based on Euclidian distances between paired vectors including intercept and trend values. These were based on 6 season relative yield values for PK, NK, and NP treatments per field, and was conducted with the 'GMD' package in R software. This clustering method starts with one cluster per field and merges clusters based on squared dissimilarities between fields, using the Ward criterion (Murtagh and

Legendre, 2014). The clustering algorithm was set to identify the number of clusters which explained at least 70% of the total variation, and additional variation explained by adding one extra cluster was less than 10%.

To evaluate the relationship between initial soil fertility and observed responses to N, P and K, seasonal RY_{PK}, RY_{NK}, and RY_{NP} values were plotted against soil organic matter (SOM), soil available P (mg kg^{-1}), and soil exchangeable K (cmol kg^{-1}) respectively. Ensuing scatter plots were then split into four quadrants by drawing a horizontal line at RY= 0.95 (where values >0.95 represented no response to the nutrient under evaluation), and vertical lines drawn at 3%, 10 mg kg^{-1}, and 0.2 cmol kg^{-1}, representing average critical values of SOM, soil available P, and soil exchangeable K respectively, for soils in the region (Okalebo *et al.*, 1993).

2.3 Results

2.3.1 Maize

Maize yields increased significantly with nutrient application including N in all six seasons (Table 2.2). In all seasons, maize yield in the control treatment was similar to that in the PK treatment, but significantly (P<0.05) less than that in the NK, NP and NPK treatments. Yields in the NK, NP and NPK treatments were not significantly different in the first season. However, NK treatment yields were significantly smaller than NPK treatment yields in all five subsequent seasons and in the last season for the NP treatment (Table 2.2). Yields in the NK treatment declined over the seasons from 5.1 to 2.9 t ha^{-1}. In the NPK treatment, yields in the long rainy seasons were at least 0.4 t ha^{-1} higher than in corresponding short rainy seasons (Table 2.2).

Table 2.2: Average maize grain yield in t ha^{-1} at 88% dry matter for nutrient omission trials conducted on 23 farms in Sidindi, western Kenya.

Treatment	Season†					
	LR 2013	SR 2013	LR 2014	SR 2014	LR 2015	SR 2015
Control	2.8^{b}	2.1^{c}	2.2^{c}	1.8^{c}	2.2^{c}	1.1^{c}
PK	3.2^{b}	2.8^{c}	2.7^{c}	2.6^{bc}	2.6^{c}	1.4^{c}
NK	5.1^{a}	3.7^{b}	3.7^{b}	3.3^{b}	4.0^{b}	2.9^{b}
NP	5.1^{a}	4.1^{ab}	4.6^{b}	4.4^{a}	4.6^{ab}	3.6^{b}
NPK	5.5^{a}	4.9^{a}	5.6^{a}	5.2^{a}	5.7^{a}	5.3^{a}
HSD	1.2	1.2	1.4	1.3	1.6	1.2

Grain yield values in the same column followed by a different superscript are significantly different at P<0.05)
HSD refers to honest significant difference between means and applies per column
†LR and SR refer to long and short rainy seasons respectively

2.3.2 Variability in grain yield responses

On average, variability was greatest in the control treatment followed by the NK treatment and least in the NPK treatment (Fig. 2.2). Variability remained constant for NPK but increased significantly (P<0.05) for only Control and NP. A decrease in variability in season five when compared to the trend was observed for all treatments except NPK which showed an increase in variability (Fig. 2.2).

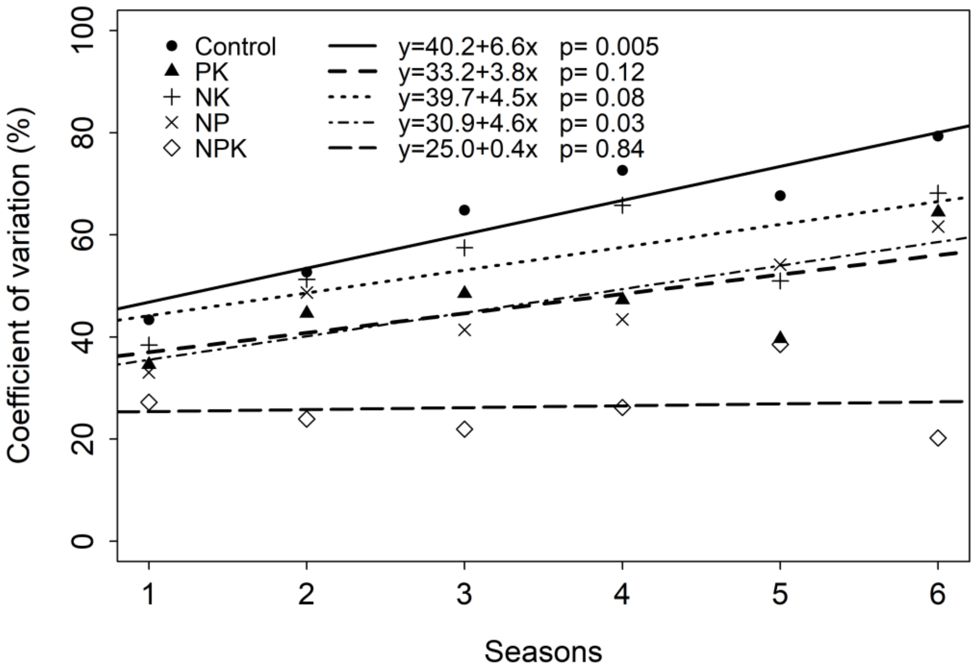

Fig. 2.2: Scatter plots of coefficient of variation in treatment maize grain yield and seasons in nutrient omission trials conducted with a single complete replicate block per farm (n = 23) in Sidindi, western Kenya. Solid and dashed lines are fitted linear regression lines. Seasons 1-6 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015 and SR 2015 respectively.

2.3.3 Maize grain yield responses to N, P and K applications

Evaluation of mean RY values in the first season showed that only $RY_{PK,}$ was significantly less than 1 (Table 2.3), indicating a strong response to only N. However, in subsequent seasons responses to N, P and K were all significant as indicated by $RY_{PK,}$ RY_{NK} and RY_{NP} values significantly less than 1 (Table 2.3), demonstrating increasing yield limitations with continued cropping without application of P and K. In all six seasons, mean RY was in the order $RY_{PK} < RY_{NK} < RY_{NP}$, indicating that N was the most limiting nutrient in the study area followed by P and K respectively.

Seasonal trends within RY showed that only in the last season was the RY_{PK} value significantly smaller than that observed in the first season, indicating minimal change in response to N over time (Table 2.3). RY_{NP} values in the third, fourth and sixth seasons were significantly (P<0.05) smaller than for the first season, while decreases in RY_{NP} were not significant over time (Table 2.3), illustrating significant temporal differences in P availability.

Table 2.3: Within and between season differences in relative maize grain yields for nutrient omission trials conducted on 23 farms in Sidindi, western Kenya.

Relative Yield†	Season‡						
	LR 2013	SR 2013	LR 2014	SR 2014	LR 2015	SR 2015	HSD
RY_{PK}	0.61^{a}	0.60^{a}	0.48^{a}	0.53^{a}	0.49^{a}	0.25^{b}	0.20
RY_{NK}	**0.93^{a}**	0.73^{ab}	0.64^{b}	0.59^{b}	0.70^{ab}	0.52^{b}	0.28
RY_{NP}	**0.94**	0.80	0.79	0.84	0.80	0.68	0.27

Values in bold are not significantly different from a value of 1
Values in the same row followed by a different superscript are significantly different at P<0.05
†*RY_{PK}, RY_{NK} and RY_{NP} are the ratios between mean PK, NK and NP treatment yield, and mean NPK treatment yield in a particular season respectively.*
‡*LR and SR refer to long and short rainy seasons respectively*
HSD refers to honest significant difference between means and applies per row

The frequency distribution of relative yield over the six cropping seasons is shown in Figure 2.3. Differences in responses to N, P and K between fields in a season were observed as well as differences in field's responses to a particular nutrient across seasons (Fig. 2.3). In the first season, strong responses to N (RY_{PK} <0.5) were observed in 29% of fields. In the subsequent five seasons, the percentage of fields strongly responsive to N (RY_{PK} <0.5) increased to 48, 57, 57, 61 and 96% respectively. For P, only 4% of fields showed a strong response to P (RY_{NK} <0.5) in the first season. In the subsequent five seasons, 22, 30, 35, 26 and 43% of fields were strongly responsive to P (RY_{NK} <0.5) respectively. RY_{NP} values in the first season indicated that only 4% of fields where strongly responsive to K (RY_{NP} < 0.5). The proportion of fields showing strong response to K (RY_{NP} < 0.5) in subsequent seasons was 17, 13, 9, 13, and 30%. Although the proportion of fields responsive to P and K were comparatively smaller than those responsive to N, the effects of P and K omission in deficient fields were very strong with yields losses of up to 80% relative to the NPK treatment in some of these farms, particularly from the second cropping season onwards (Fig. 2.3b, 2.3c, 2.3d, 2.3e and 2.3f).

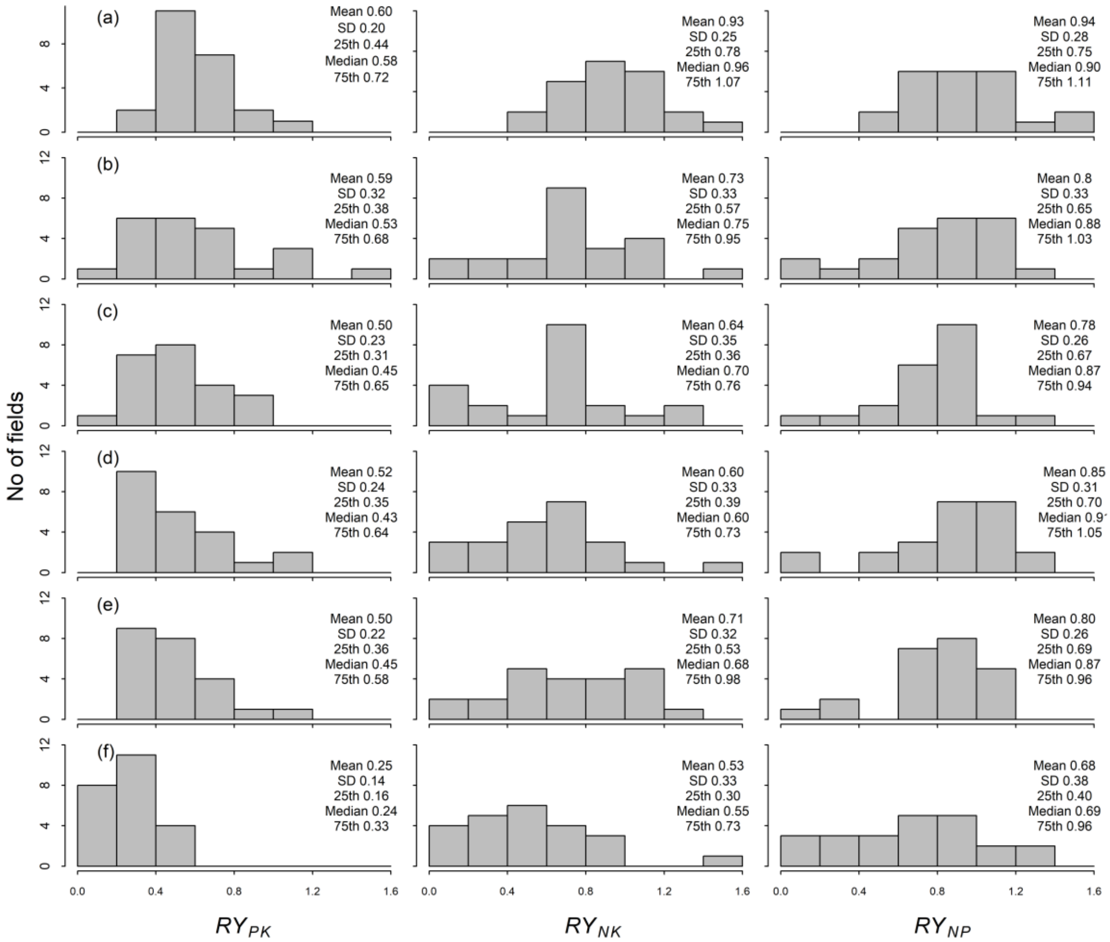

Fig. 2.3: Frequency distribution plots showing relative maize grain yield RY_{PK}, RY_{NK} and RY_{NP} in nutrient omission trials conducted with a single complete replicate block per farm (n = 23) in Sidindi, western Kenya in: (a) long rains 2013; (b) short rains 2013; (c) long rains 2014; (d) short rains 2014 seasons; (e) long rains 2015; and (f) short rains 2015 seasons respectively. RY_{PK}, RY_{NK} and RY_{NP} are the ratios between PK, NK and NP treatment yields and NPK treatment yield respectively.

2.3.4 NPK response clusters

Six clusters with high internal homogeneity explaining 75% of total variation in yield trends (not shown), were identified to categorize fields in the study area into N, P and K response classes (Fig. 2.4). Clusters clearly differed in RY of control plots and NPK response (Fig. 2.4). Overall, RY_{PK} declined over time for all clusters, while RY_{NK} declined over time in 5 out of 6 clusters indicating increased deficiency of N and P due to nutrient mining (Fig. 2.4b and 2.4c). However, clusters RY_{PK} converged, while RY_{NK} diverged over time (Fig. 2.4b and 2.4c), indicating differences in response patterns between nutrients over time. Negative trends in RY_{NK} for clusters 2, 3, 4 and 6 indicated limited P stocks (Fig. 2.4c). However, declines for clusters 2 and 4 stabilised from season 3 onwards (Fig. 2.4c). RY_{NK} for cluster 1 did not show strong trends at levels of about 0.75, indicating P deficient conditions with resilient P stocks (Fig. 2.4c). A negative RY_{NP} trend in cluster 1 indicates an increasing K deficiency, while clusters 1 and 4 were somewhat deficient, although deficiency did not increase much over the seasons (Fig. 2.4d). The strongest response to K supply was observed for fields in cluster 6, and fields in clusters 1, 2 and 4 also benefited from K supply, as shown by RY_{NP} values below 1.0 for most seasons (Fig. 2.4d). Cluster 5 included four farms with low relative yield values for the control and PK treatments, while relative yields in the NK and NP treatments were around 1.0 in all seasons indicating N deficiency while P and K supply was sufficient for all seasons (Fig. 2.4a, 2.4b, 2.4c and 2.4d).

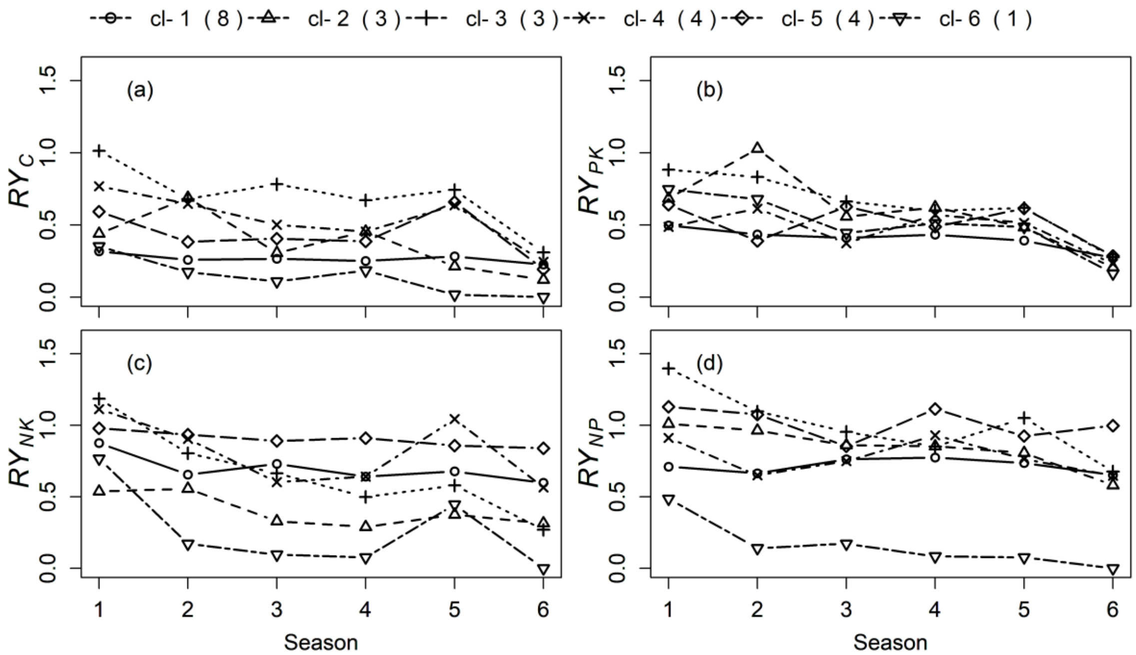

Fig. 2.4: Seasonal trends in relative yields (RY) per cluster for: (a) control; (b) PK; (c) NK; and (d) NP treatments respectively. Seasons 1-6 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015 and SR 2015 respectively. 'RY_C', 'RY_{PK}', 'RY_{NK}' and 'RY_{NP}' are the ratios between control, PK, NK and NP treatment yields and NPK treatment yield respectively.

Consistency of spatial patterns was evaluated using normalized treatment yields (Fig. 2.5). A large range in NY values and consistent differences between clusters were observed for control, PK, and in particular NK treatment yields, indicating strong and persistent spatial yield patterns. The range in NY values for the NPK treatments was much smaller (Fig. 2.5b). This illustrates that spatial differences between trend clusters were mainly driven by differences in field P availability (Fig. 2.5a, 2.5c, 2.5d and 2.5e), and amendments with NPK reduce spatial variability.

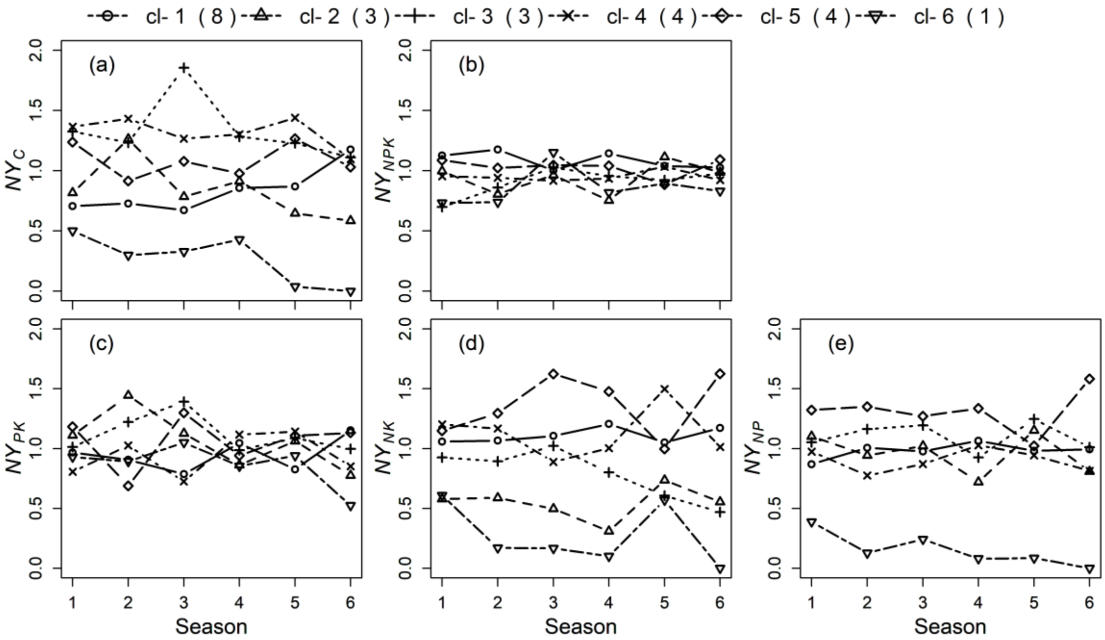

Fig. 2.5: Seasonal trends in normalized yields (NY) per cluster for: (a) control; (b) NPK; (c) PK; (d) NK; and (e) NP treatments respectively. Seasons 1-6 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015 and SR 2015 respectively. *'NY_C', 'NY_{PK}', 'NY_{NK}', 'NY_{NP}'* and *'NY_{NPK}'* are the ratios between field level control, PK, NK, NP and NPK yield and seasonal means of control, PK, NK,NP and NPK yield respectively.

To assess if yields in unfertilized plots would be a good predictor for the response to NPK, seasonal relative control, PK, NK and NP treatment yields were plotted against seasonal normalized control yields (Fig. 2.6). Normalized control treatment yields were shown to provide a good indicator of the response to combined NPK application, with farms with high control yields showing a weaker response to combined NPK application (Fig. 2.6). Control yields were however less informative for responses to other treatments. The range of normalized control yields increased over time indicating increasing differences in nutrient depletion rates in the various fields over time (Fig. 2.6).

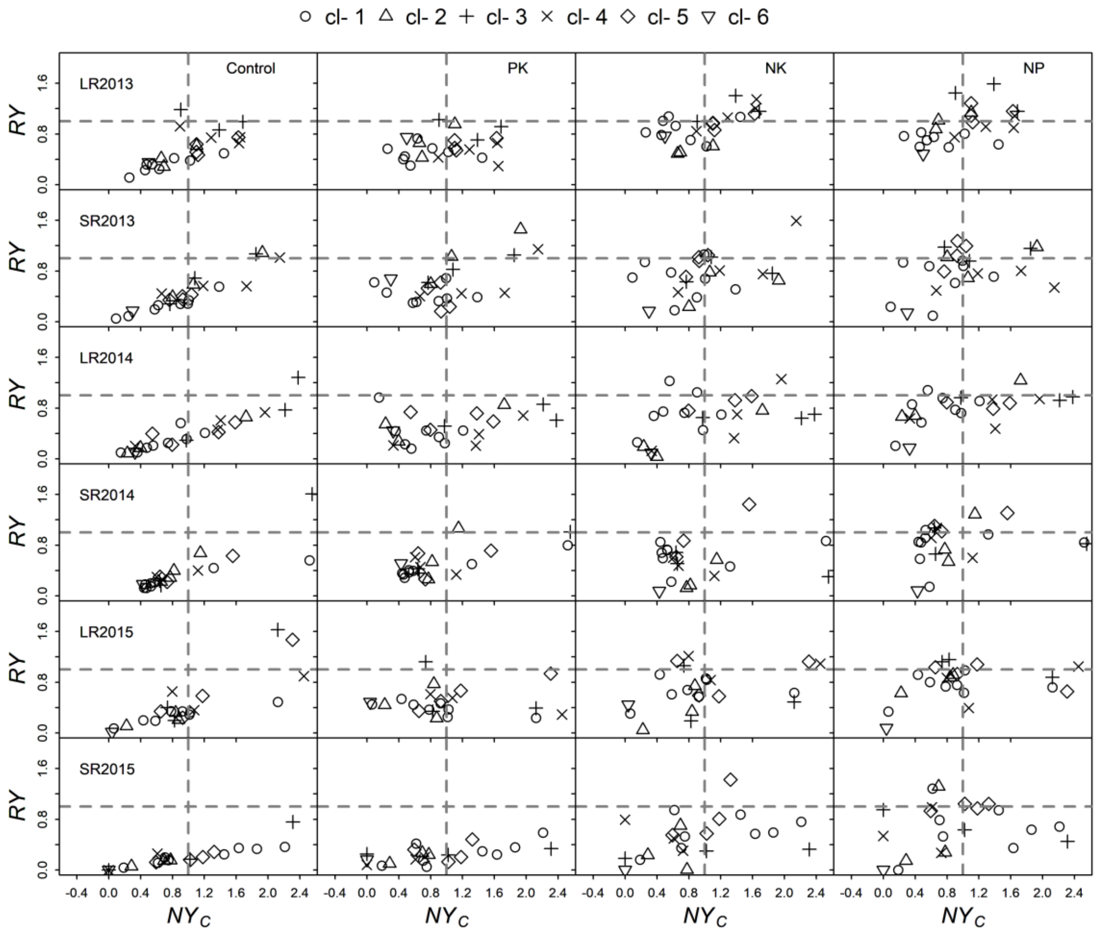

Fig. 2.6: Relative yields (RY) of control, PK, NK and NP treatments versus normalized control treatment yields (NY_c) for fields in the identified clusters. LR and SR refer to long and short rains seasons respectively.

2.3.5 Relationship between soil fertility and responses to NPK

All fields in the experiment had a sandy loam, sandy clay loam or sandy clay texture, with contents ranging from 16.5 – 38.5 % clay, 6.2 – 19.8 % silt and 48.0 – 77.2% sand. Response to N was weakly related to soil SOM content (Fig. 2.7a). The majority of RY_{PK} values were within the N deficiency range across the extent of soil organic matter values (Fig. 2.7a). At low available P values (<10 mg kg^{-1} P) response to P was weakly related to available P with low and high RY_{NK} values observed across the range of available P values (Fig. 2.7b). However, at larger available P values (>10 mg kg^{-1} P) RY_{NK} values indicated minimal P deficiency across the six seasons study period (Fig. 2.7b). Responses to K varied greatly over the range of exchangeable K values measured, with some high RY_{NP} values observed at low exchangeable K values, and low RY_{NP} values observed at higher exchangeable K values (Fig. 2.7c). However, the majority of RY_{NP}

values indicated K sufficiency conditions. Mean soil properties did not show significant differences between clusters (not shown).

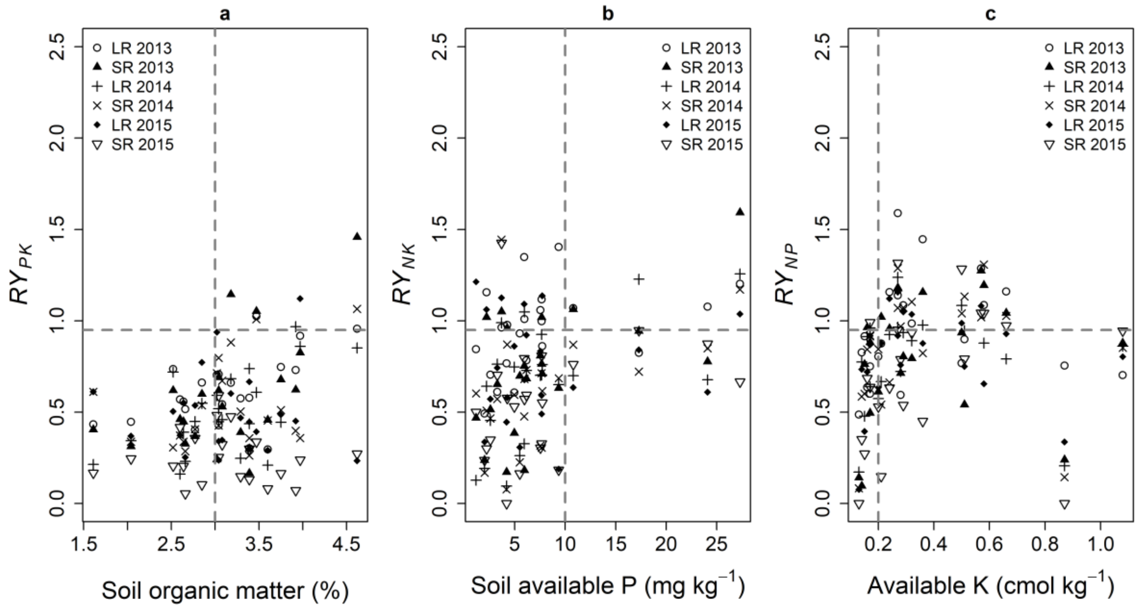

Fig. 2.7: Relationships between: a) soil organic matter content (%) and relative PK treatment yield (RY_{PK}); b) soil available P (mg kg^{-1}) and relative NK treatment yield (RY_{NK}); and c) soil exchangeable K (cmol kg^{-1}) and relative NP yield (RY_{NP}), across 23 fields in four consecutive cropping seasons in Sidindi, western Kenya. Horizontal dotted lines represent relative yield = 0.95, while vertical dotted lines represent critical values for respective soil properties.

2.4 Discussion

The observed maize yield responses to the applied N, P and K combinations were highly variable over space and time, confirming the strong effects of the variability in soil fertility on maize productivity and nutrient requirements. N was deficient on most farms, while the responses to P and K application varied strongly across farms. Temporal differences in response to N were weak as illustrated by the minimal change in mean RY_{PK} over time, and the gradual decline in RY_{PK} observed for most clusters. Spatial differences in response to N also decreased over time as illustrated by the observed convergence in RY_{PK} for the different response clusters over time. The widespread N deficiency can be linked to the relatively low soil organic matter contents resulting from continuous cropping without legumes and very limited application of fertilizer N or manure (Tittonell *et al.*, 2005b; Shepherd and Soule, 1998). Combined application of fertilizer N with organic resources (Vanlauwe *et al.*, 2011) and rotation of cereal crops with legumes (Tully *et al.*, 2015) can help farmers in this region improve the N status of their farms across the response clusters. Given the minimal spatial-temporal differences in response to N observed, we expect minimal improvements in nitrogen use efficiency when accounting for differences in spatial temporal responses to N between farms in the Siaya region.

Large relative NK yields indicated that maize yield response to applied P was not significant in the first season. This was likely due to some residual effect of P applied in previous seasons, as P applied as fertilizer or manure that is not taken up by the crop is released slowly to succeeding crops (Janssen *et al.*, 1987; Kifuko *et al.*, 2007). The presence of clusters with large differences in the response to applied P, and the large variability in NK treatment maize yields that we observed indicates differences in P fertility status of the soil, reflecting differences in historical field management and farmer resource endowment (Vanlauwe *et al.*, 2006). However, residual P was only effective over a short period of time, with more farms showing stronger responses to P over time. This shows that resilience of soil P stocks in these fields is limited. Omitting P for more than one season resulted in significant and progressively smaller yields when compared to P fertilized plots. The small rates of fertilizer applied by smallholder farmers in western Kenya are insufficient to build soil P availability that can support high maize yield for multiple seasons (Kamiri *et al.*, 2011; Kihara and Njoroge, 2013). Judicious and regular application of P, whether seasonally or every second season based on observed response clusters can therefore assist farmers to sustain productivity.

Strong spatial-temporal patterns in response to K were observed. Two out of 23 fields showed very strong response to K, while declining relative yields for the NP treatment were observed in Clusters 1, 2 and 4 which included 65% of fields in the study area. Further, K deficiencies are expected to become more pronounced at higher N and P application rates. These findings are in contrast to current fertilizer recommendation for the Siaya region which assume sufficient K reserves (FURP, 1994), and could be related to the presence of localized K deficiency hotspots (Kihara *et al.*, 2016), and continuous removal of harvest products without application of mineral K (Chianu and Mairura, 2012; Zörb *et al.*, 2014). Crop productivity intensification strategies based on increased fertilizer application should therefore be cognisant of the need to supply K in combination with N and P, even in regions that are traditionally considered to be mainly deficient in N and P, such as western Kenya. Targeted application of K fertilizer to K deficiency hot spots is also recommended (Kihara *et al.*, 2016).

The assessment of soil nutrient status has been identified as a key starting point in the process of restoring and managing soil fertility (Sanginga and Woomer, 2009). Soil available P following Mehlich-3 extraction has been found to reliably estimate plant available soil P levels (Mehlich, 1984), while soil exchangeable K is usually used as the basis for K fertilizer recommendations (Madaras and Koubová, 2015; Zörb *et al.*, 2014).

However, soil organic matter, soil available P, and soil exchangeable K related weakly to responses to N, P and K respectively. Weak relationships were previously reported by Vanlauwe *et al.* (2006), with soil total N explaining only 27% - 44% of the response to N, while crop yield response to P did not increase beyond an Olsen-P value of 8 mg kg^{-1}. In the same study area, Tully *et al.* (2015) observed large variation in maize yields between 24 farms despite largely similar soil physical and chemical properties between farms. Working across various sites in SSA, Kihara *et al.* (2016) reported minimal variation in exchangeable Mehlich K despite strong responses to K in some sites, while soil organic carbon (SOC) was not a defining factor for different nutrient response classes observed. Given that soil analysis data was weakly related to the observed differences in responses to applied N, P and K, the merit of deriving fertilizer recommendations based solely on field-level soil analysis can be questioned. It is noted that soil analysis was only conducted at the start of the experiment and hence did not allow for a detailed analysis of the dynamics of soil nutrient changes and responses to nutrients. However, this analysis provides a fair evaluation of the value of soil analysis for majority of smallholder farmers as for practical reasons, most farmers will assess the soil P and K fertilizer status only once every few years. Results from this study indicate that while soil analysis may be helpful to monitor soil nutrient stocks, it does not provide sufficiently reliable quantitative information that can be used to adjust required inputs. A strategy to fertilize the soil to maintain moderate P and K stocks, balancing in- and outputs, while fertilizing the plant with minimum side-dress PK mix at planting and top-dressing of N would be recommended. In addition, the restoration of soil P and K stocks based on the field history, including socio-economic and rock mineralogical factors is recommended as these factors have previously been identified as drivers of variability in yield response (Tittonell *et al.*, 2008a; Zingore *et al.*, 2011).

Cluster analysis allowed identification of distinct N, P and K response categories that differed in response to fertilizer application and the resilience of soil nutrient stocks. All fields in this study were responsive to combined NPK fertilizer (Kihara *et al.*, 2016; Zingore *et al.*, 2007b), where the response was strongly related to yield in control plots. The presence of distinct N, P and K response clusters calls for site specific nutrient recommendations that address the observed variability. For example, based on observed N, P and K response patterns, improved nutrient allocation strategies based on differential N, P and K rates and combinations can be formulated to meet either short or long term crop productivity intensification objectives at the farm level. Such strategies can be designed using tools such as Nutrient Expert (Pampolino *et al.*, 2012) and FIELD (Tittonell *et al.*, 2010a).

A major challenge exists in the identification of response patterns at scale. Recent developments in the use of satellite data offer an opportunity to assess and quantify spatial heterogeneity at regional scales (Lobell, 2013; Shanahan *et al.*, 2001). At the local level, farmers have shown the ability to categorize their farms into relatively homogenous entities using criteria such as crop performance, ease of tillage, soil moisture retention, soil colour and presence of weeds and soil invertebrates (Murage *et al.*, 2000), and this has being suggested as key for designing strategies for improved crop productivity in the region (Tittonell *et al.*, 2013).

The consistently higher average NPK treatment yields relative to other treatment yields observed, coupled with the lowest variability in yield observed for this treatment indicates that amendment with NPK helps to reduce observed spatial-temporal variability. This highlights the importance of balanced nutrient management to increase and stabilize yield across wide-ranging soil fertility conditions. The NPK treatment yielded on average 0.5-1.7 t ha^{-1} more than the NP treatment, a significant difference in 2 out of the 6 seasons. The main current mineral fertilizer use recommendation in the Siaya region of 55 kg N and 25 kg P ha^{-1} (FURP, 1994) needs to be revisited. Results in this experiment indicate that yields above 5 t ha^{-1} can be sustained using the short season cultivar, where nutrient use efficiency can be further improved when accounting for comparative yield levels in control plots without fertilizer application. Results in this study further indicated that maize yield response to combined NPK application was higher in long rainy seasons, illustrating that there may be room for farmers to further improve the efficiency of fertilizer use through fertilizer application rates based on in-season rainfall (Kurwakumire et al., 2014; Van Ittersum et al., 2016). There is therefore potential for majority of farmers in the Siaya region to surpass the initial target of 3 t ha^{-1} set towards achieving the African Green Revolution (Sánchez, 2010) in the face of variable responses to N, P and K.

2.5 Conclusions

We conclude that strong spatial-temporal differences in responses to N, P and K exist in smallholder farming systems in western Kenya. It is clear that current blanket fertilizer application rates result in low nutrient use efficiencies and may not achieve the desired sustainable crop productivity improvement in the region. We further conclude that current soil analysis techniques were not able to adequately predict the crop response that can be expected from N, P and K fertilizers. This raises questions whether investing in soil analysis alone results in better fertilizer recommendations for smallholder farmers, and urges for a new, more cost-effective approach. The strong spatial-temporal patterns observed indicate that characterization of soil, lithological and landscape characteristics in combination with management history may result in a much cheaper and more cost-effective methodology for assessing the required N, P and K fertilizer applications, when mapped at the appropriate scale. Decision support tools may offer a feasible and cheaper alternative for the development of site-specific nutrient recommendations using information readily available at the farm level. In the absence of such strategies, balanced nutrition including N, P and K offers farmers in heterogeneous landscapes a lower risk intensification option that results in yields that can be sustained during a much longer period of time, evidenced by the relatively small variations in yield for the NPK treatment across fields and seasons.

2.6 Acknowledgement

This study was facilitated through funding from Agrium to the International Plant Nutrition Institute (IPNI), for research on 4R Nutrient Stewardship in western Kenya.

Learning from the soil's memory: Tailoring of fertilizer application based on past manure applications increases fertilizer use efficiency and crop productivity on Kenyan smallholder farms

This chapter is published as:

Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2019. Learning from the soil's memory: Tailoring of fertilizer application based on past manure applications increases fertilizer use efficiency and crop productivity on Kenyan smallholder farms. European Journal of Agronomy 105, 40-53

Abstract

The large uncertainty in yield response to fertilizer application within smallholder cropping systems in sub-Saharan Africa (SSA) limits efforts aimed at intensifying crop production based on increased fertilizer application. We assessed the key field-scale driver of variability in maize (*Zea mays L.*) grain yield response to fertilizer nitrogen (N), phosphorus (P) and potassium (K) in the Sidindi area of western Kenya based on past manure application, distance from the homestead, and clay and silt contents. We used data from nutrient omission trials conducted on 23 farms over seven consecutive cropping seasons covering the period 2013–2016, without changing treatments or plot location. Treatments included a control and PK, NK, NP and NPK. Accounting for past manure application increased the explained variability in maize yield, and yield response to N, P, and K application. Mean treatment maize grain yield in the control, PK, NK, NP and NPK treatments were 1.0, 2.2, 1.5, 2.9 and 4.5 t ha^{-1} at 88% dry matter respectively in fields without past manure application, and 2.4, 2.7, 4.4, 4.9 and 5.4 t ha^{-1} in fields which had received animal manure in at least two out of three seasons prior to the start of the trials. Mean maize yield response to N, P and K application was 2.3, 3.0 and 1.6 t ha^{-1} respectively in fields without past manure application, and 2.8, 1.1 and 0.6 t ha^{-1} in fields with past manure application. In the seventh cropping season, past animal manure application contributed a fertilizer equivalent of 28.3, 29.8 and 31.5 kg ha^{-1} of N, P and K, respectively. At both the onset and at the start of the last season, fields with past animal manure application had on average higher contents of SOC, available P and exchangeable K, yet differences were not always significant within treatments. Accounting for past animal manure application reduces crop fertilizer requirements for P and K as well as decreasing uncertainty in yield response to fertilizer. We conclude that the strong influence of past animal manure application on yield response to fertilizer application merits the inclusion of past manure application as a co-variate in analysis of yield response data from smallholder cropping systems of SSA.

Key words: Yield response to fertilizers, past manure application, sub-Saharan Africa

3.1 Introduction

Increased fertilizer use is key to increase crop productivity in smallholder farming systems of sub-Saharan Africa (SSA) (Vlek, 1990). Yet crop yield response to fertilizer is highly variable across and within fields on smallholder farms even when management is optimal (Kihara *et al.*, 2016; Njoroge *et al.*, 2017b; Xu *et al.*, 2015). At the regional scale, variability in yield responses to fertilizer use across smallholder farming systems is mainly related to differences in soil types resulting from differences in: parent material; climate; position of the landscape along the catena; and other factors influencing the soil formation process (Deckers, 2002). At local scales, variability among farms is mainly driven by management (Zingore *et al.*, 2007b). Such variability has a substantial impact on the efficiency and profitability of fertilizer use (Vanlauwe *et al.*, 2011), which may in turn influence the decisions of farmers whether or not to invest in fertilizer. Efforts aimed at enhancing crop productivity in smallholder farms of SSA should therefore be cognisant of such management-driven variability in crop response to fertilizers, in addition to agro-ecological conditions (Nyamangara *et al.*, 2011).

Contrasting effects of past management on yield response to fertilizer have been observed. In western Kenya, Vanlauwe *et al.* (2006) reported a stronger yield response to fertilizer applications in outfields compared with homefields. This was linked to gradients of decreasing soil fertility with increasing distance from the homestead resulting from preferential allocation of organic resources such as manure in nearby fields (Tittonell *et al.*, 2005b; Vanlauwe *et al.*, 2006). In contrast, in Zimbabwe, (Zingore *et al.*, 2007b) found stronger yield responses in homefields compared with outfields. This was linked to severe soil degradation in the outfields due to continuous cropping without organic resources (Zingore *et al.*, 2007b). Preferential allocation of nutrient resources to fields perceived to be more fertile by farmers at the expense of those perceived to be less fertile further reinforces soil fertility patterns within farms (Tittonell *et al.*, 2008a), resulting in increased variability in yield response to applied fertilizers between fields. The studies above illustrate clearly that the available fertilizer resources can be employed tactically to enhance nutrient use efficiencies by resource constrained farmers (Kurwakumire *et al.*, 2014; Tittonell and Giller, 2013).

The tactical application of available fertilizer resources for enhanced nutrient use efficiency fits within the integrated soil fertility management (ISFM) approach which seeks to maximize the agronomic efficiency (AE) of applied fertilizers and improve crop production (Vanlauwe *et al.*, 2015). In this approach, improvements in AE are achieved through adaptation of fertilizer and agronomic practices to local conditions (Vanlauwe *et al.*, 2015). Extension advisors in smallholder farming systems of SSA lack decision support tools to assist farmers achieve such adaptation. For the successful development of such tools, identification of the key factors driving variability in yield response to nutrient applications under a given set of field and management conditions is required.

Results from multiple on-farm nutrient omission trials over multiple seasons on smallholder farms in western Kenya showed strong spatial-temporal patterns in maize yield response to applied N, P and K (Njoroge *et al.*, 2017b). Observed patterns in yield response and the efficiency of fertilizer use could not be fully explained using soil analysis data (Njoroge *et al.*, 2017b). Given the strong spatial-temporal patterns observed, this dataset forms a good starting point for the detailed assessment of the key management and field attributes that drive variability in response to applied N, P and K over time. Our specific objectives were to: (i) identify the key drivers of variability in maize yield response to fertilizer N, P and K application at the field level; to (ii) quantify the specific contribution of these key drivers to variability in maize yield response to applied N, P and K; and to (iii) identify the contribution of these key factors to processes driving variability in maize yield responses to N, P and K application over time. We hypothesized that long-term variability in yield response to applied fertilizers among fields and farms is mainly driven by differences in past farm management.

3.2 Materials and methods

3.2.1 Study area, site selection, and field experiments

The study was conducted in Sidindi area in Siaya County, western Kenya, at a latitude of 0.15 ^{o}N, a longitude of 34.4 ^{o}E and at about 1240 metres above sea level. Annual rainfall ranges from 1600 – 2000 mm and is distributed over two distinct seasons with a long rainy (LR) season from March to July, and a short rainy (SR) season from September to December. Full details on the study area, characteristic and selection of the sites, and field experiments are provided in Chapter 2. In summary, nutrient omission trials were established at the onset of the long rainy season in 2013 on 23 different farmers' fields considered representative of the study area based on socio-economic characteristics and soil conditions. Field selection was additionally based on field location in relation to the landscapes, with fields on valley bottoms and steep slopes avoided to limit effects of; nutrient influx and waterlogging in valley bottom fields, and nutrient losses through runoff in fields on steep slopes. In each farm, urea, triple super-phosphate (TSP) and muriate of potash (MOP) were used as N, P and K sources respectively to establish a set of five treatments including (i) control (no nutrients added), (ii) PK (40 kg P ha^{-1} + 60 kg K ha^{-1}), (iii) NK (150 kg N ha^{-1} + 60 kg K ha^{-1}), (iv) NP (150 kg N ha^{-1} + 40 kg P ha^{-1}), and (v) NPK (150 kg N ha^{-1} + 40 kg P ha^{-1} + 60 kg K ha^{-1}) in plots measuring 10 m by 10 m, with maize as the test crop. Nutrients were applied at rates sufficient to achieve yields of 5-6 t ha^{-1} in the balanced NPK treatment. The same treatments were established on each farm without replication i.e., one set of treatments was established on each farm. N was applied in three equal splits; at planting, at three weeks after emergence and at six weeks after emergence, while all P and K was applied at planting. Trial plot locations and allocated treatments remained the same throughout the study period over seven seasons (long rains 2013 to long rains 2016). Throughout the experimental period, the short-season maize variety DK8031 was sown at the recommended spacing (75 × 25 cm) to give 53,333 plants ha^{-1} after thinning. Two seeds were sown per planting station and thinned to one plant at two weeks after emergence. All plots were manually weeded at three and six weeks after emergence.

3.2.2 Soil sampling and analysis

Soil sampling and analysis was conducted at the onset and end of the experimental period. In February 2013, one composite soil sample was collected for each field using a 'Y frame sampling approach', taking samples at 0-20 cm depth. Processed samples were analysed at Crop Nutrition Laboratories in Nairobi for available P and exchangeable bases following a Mehlich 3 extraction (Mehlich, 1984) and soil organic carbon (SOC) using the Walkley-Black wet oxidation method (Anderson and Ingram, 1994).

Prior to the start of the long rainy season in 2016 (February 2016), a second set of soil samples was collected and analysed, but now a sample was taken per plot. For this, composite soil samples were collected from each plot in all fields to give a total of five samples per field. In each plot, soil samples were collected from four points using a 'Y frame approach' at 0-20 cm depth. Collected samples were subsequently placed in a bucket and mixed thoroughly before the composite sample was taken. These samples from each plot were air dried and passed through a 2 mm sieve prior to chemical analysis at the Lancrop Laboratories in the United Kingdom. Total nitrogen (N), available phosphorus (P), and soil organic carbon (SOC) were analysed using the Kjeldahl method, modified Olsen, and Walkley-Black methods respectively (Anderson and Ingram, 1994). Exchangeable bases (Ca, Mg, K and Na) were determined using atomic absorption spectrometry using ammonium nitrate as the extracting agent. For both sampling periods, soil pH was determined in water using the pH electrode method with a ratio of 1:2.5, while soil texture was determined using the improved hydrometer method (Bouyoucos, 1962).

3.2.3 Farm management survey

At the onset of the first cropping season, a survey was conducted to obtain information on key farm management practices for the past three seasons in the specific field where the experiment was located. The survey was conducted using structured questionnaires to interview the key decision maker on the farm. Local enumerators and extension officers conversant in the local language and farming system were trained and engaged to administer the questionnaires. Information collected included details on: cropping system used; crop residue management practices; main crops cultivated; livestock manure application history in the past three years; and fertilizer types and amounts applied in the last main cropping season before the experiment was established. A short review of the answers provided was conducted by walking through the experimentation field together with the farmer who further explained and illustrated management practices conducted. The distance from the farmer's homestead to the experimental field was determined by measuring the shortest accessible path from a central position in the homestead to the field using calibrated twines.

3.2.4 Grain yield

Each season, maize was harvested at physiological maturity within a net plot of 2.25 m by 3 m including three centre rows in each plot, leaving at least 2 m on each side of the centre rows to minimize edge effects. After harvesting, total plant and cob numbers were recorded, and total cob weight determined in the field using a digital scale accurate to 2 decimal places. Grain moisture content was determined using a moisture tester (Dickey John Mini GAC, Minneapolis USA). Grain yield in each plot was then converted to yield per hectare on a 12% moisture basis.

3.2.5 Total nutrient uptake

In the final season (LR 2016), stover biomass was determined to allow for evaluation of total nutrient uptake in the aboveground biomass. For this, all stover material from the harvested net plot was weighed using a spring balance after detaching maize cobs, and stover weight per plot was recorded. Subsequently a sample of the stover was taken by selecting five representative plants. These were then cut into 5 cm pieces and well mixed before a subsample of 200 g was weighed using a digital scale, and placed in a clearly labeled sample bag for further drying and processing. This subsample was air-dried to a constant weight, and weights and the mass fraction of air-dry stover in fresh material were determined and used to calculate air dry stover yield (t ha^{-1}).

Nutrient uptake in grain and stover was calculated following determination of grain and stover nutrient concentrations at the Lancrop Laboratories in the United Kingdom. For this, representative subsamples of the air-dried stover and grain were oven dried for 48 hours at 60 °C and then ground to pass a 1 mm screen. Total grain and stover nitrogen (N) contents were determined using the Kjeldahl method following digestion with sulphuric acid (Miller and Horneck, 1997), while the other macro and micronutrients were determined by inductively coupled plasma emission spectrometer following ashing at 500 °C and digestion in concentrated hydrochloric acid (Isaac and Johnson, 1997). Nutrient uptake in grain and stover were determined as a function of grain and stover nutrient concentrations, and grain and stover dry matter yields respectively. Total nutrient uptake for each nutrient was then calculated as the sum of grain and stover nutrient uptake in each treatment plot.

3.2.6 Statistical analysis

To assess the long-term effects of different nutrient combinations on observed maize yield, effects of treatments imposed were evaluated as the deviations in yield for these treatments from yield observed in the NPK treatment. For this, a mixed effects linear model with grain yield as the response variable, and treatment and season number as fixed effects was fit using the 'lme4' package in R software (Bates *et al.*, 2015; R Core Team, 2017). Variation in grain yield due to differences in farms and season type (long and short rains) was accounted for by including these as random effects in the mixed model. Significant effects of model parameters on grain yield were evaluated using the 'lmerTest' package in R software (Kuznetsova *et al.*, 2017).

Classification and regression tree (CART) analysis with the 'rpart' (Therneau *et al.*, 2017) and 'rpart.plot' (Milbrow, 2017) packages in R software was used to identify the key field or management factor driving variability in yield response between farms. CART analysis has been previously used in the identification of key variables driving variability in yield response to applied nutrients between farms (Steinberg, 2009) and is especially useful due to its ability to handle both numeric and non-numeric data (Tittonell *et al.*, 2008a). For this, a dataset (n=799) comprising of normalized maize grain yield for the control, PK, NK, NP and NPK treatments established in 23 fields across seven cropping seasons was used. Normalized yield (NY) was determined as the ratio between the yield for a particular treatment and season in a particular field, and average treatment yield for that treatment across all fields in a particular season. Yield normalization allows for comparison among plots, and enables understanding of key factors that may identify better performing plots. This dataset excluded six cases where yield data was missing due to erroneous harvesting of some trial plots by farmers in one of the seasons. In the CART model developed, percentage clay and silt content, past manure application history, and field distance from the homestead (m) were used as explanatory factors representing: soil type, previous farm management, and field characteristics respectively. To quantify the effect of key field or management factors on yield response to applied N, P and K, a new mixed effects model was constructed by including the key factor identified using the CART analysis as a fixed effect in the initial yield mixed effects model. The additional effect of the new factor on yield response was evaluated using the 'lmerTest' package in R, and the new model evaluated for improved model fit using the Akaike information criterion (AIC) in R software. Temporal variability in plant response to N, P and K application in relation to the key factor identified was also assessed. Differences in total plant nutrient uptake and mean soil properties in the last cropping season were also evaluated using the final model developed. For this, the fixed and random effects of season number and season type respectively were removed as treatment level nutrient uptake data and soil properties data were only available for the last season. Mean mixed models estimates of treatment grain yield and treatment nutrient uptake were subsequently used to assess differences in nutrient availability in the full NPK treatment for fields with and without past manure application based on physiological nutrient use efficiency (PhE). PhE is the ratio of grain yield (DM kg ha^{-1}) to the total nutrient uptake (kg ha^{-1}) (Janssen, 2011). To assess differences in soil nutrient supply based on past manure application, estimated mixed model mean soil property values were used to determine potential supplies of soil N, P and K. Based on these potential supplies, the related fertilizer N, P and K equivalent values were calculated. This was achieved using equations for potential soil nutrient supply and fertilizer equivalent from the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model (Janssen *et al.*, 1990), with updated parameter sets derived from Sattari *et al.* (2014). The QUEFTS model uses empirical relationships to calculate the potential soil supply of N, P and K based on measured soil chemical properties, and has been widely applied to appraise the status of N, P and K in soils under tropical conditions (Janssen *et al.*, 1990). Mixed model mean estimates of soil P and K were further used to estimate within treatment differences in total soil P and K contents in the top soil layer (0 – 20 cm) based on past manure application. Total soil nutrient content in the top soil layer was calculated as a function of mean soil nutrient content in milligrams per kilogram, and total quantity of soil in the top soil layer in kilograms per hectare. For P, the estimated mean Olsen P value in mg kg^{-1} for each treatment and manure use category was used. For K, mean estimated exchangeable K values in cmol kg^{-1} were converted to exchangeable K in mg kg^{-1}, and these values subsequently used to estimate the total K contents in the top plough layer. Total quantity of soil in the top soil layer (0.2 m depth) was estimated at 3,000,000 kg ha^{-1} by assuming a bulk density of 1.5 g cm^3 for the sandy clay soils in the study area.

3.3 Results

3.3.1 Farm characterization

Results from the agronomic survey indicated all farmers had similar cropping systems and crop residue management (not shown). All farmers in the study intercropped cereals and legumes; notably maize and bush varieties of common bean (*Phaseolus vulgaris* L.). Crop residues were removed from all of the fields immediately after harvesting. Farmers predominantly used DAP and CAN fertilizer as basal and top dressing respectively. However, review of data collected using questionnaires, and from further discussions with farmers revealed major inconsistencies in quantities of fertilizers reported to be used in the past within the experimental fields. As such, data on previous fertilizer use was not used in explaining observed yield responses. Some 70% of the farmers reported frequent manure application, and had applied manure in the field where the experiment was located in at least two of the previous three seasons prior to the study. The remaining 30% had not applied manure in the field where the experiment was located in the previous three seasons, and did not usually apply any manure in their farms due to unavailability. Average distance between the experimental fields and the farmers' homestead was approximately 75 m. All fields in the study were cropped in both the long and short rainy seasons with no fallow periods, and had been under cultivation for >20 years.

3.3.2 Soil characterization

Soils in the study area are sandy clays with moderate clay and silt contents (Table 3.1). Mean soil pH, soil organic carbon, available P, and exchangeable K contents were generally larger for fields with past manure application (Table 3.1). Wide ranges in values for soil organic carbon and macronutrients contents were however observed within the two past manure application categories.

3.3.3 Effect of nutrient applications on maize yields

Mean estimated yield over the seven seasons in the NPK treatment was 5.4 t ha^{-1} (Table 3.2). This did not vary significantly over time as indicated by the estimate and p value associated with the season number and NPK interaction parameter (Table 3.2). Maize grain yield was significantly ($P<0.05$) reduced by 2.7, 2.3 and 0.9 t ha^{-1} in the control, PK, and NK treatments respectively, when compared to the NPK treatment (Table 3.2). A significant (*P<0.05*) decline in yield over time was only observed in the control and NK treatments. Yields declined most strongly over time in the NK treatment by 0.3 t ha^{-1} per season compared with the decline of 0.1 t ha^{-1} per season in the NPK treatment (Table 3.2). The yield difference between the NPK and NK treatments, therefore increased from 0.9 t ha^{-1} in the first cropping season, to 2.3 t ha^{-1} in the seventh cropping season.

Table 3.1: Mean and range of soil properties (0 – 20cm) for fields with and without past manure application at the start of nutrient omission trials in Sidindi, western Kenya. (n = 23).

Past	Soil properties								
	pH	OC	P	K	Ca	Mg	Na	CEC	Clay + Silt
	(1:2.5 H_2O)	(g kg^{-1})	(mg kg^{-1})	(cmol kg^{-1})	(cmol kg^{-1})	(cmol kg^{-1})	(cmol kg^{-1})	(cmol kg^{-1})	(%)
(-) Manure (n=7)	5.7	16.4	4.7	0.3	5.2	1.9	0.1	10.9	44.7
	(5.1 – 6.1)	(9.3 – 22.7)	(1.2 – 9.4)	(0.1 – 0.9)	(2.8 – 7.7)	(1.2 – 2.9)	(0.1 – 0.2)	(7.0 – 15.5)	(40.3 – 48.6)
(-) Manure (n=16)	5.8	18.5	8.5	0.4	4.9	1.8	0.1	9.8	40.6
	(5.3 – 6.4)	(14.6 – 26.8)	(2.0 – 27.3)	(0.2 – 1.1)	(1.8 – 9.6)	(0.8 – 3.0)	(0.1 – 0.2)	(4.4 – 16.9)	(22.7 – 51.9)

Table 3.2: Mixed model parameter estimates with standard errors (SE) of the long term effect of nutrient additions on maize grain yield in t ha^{-1} per season at 88% dry matter in nutrient omission trials conducted on 23 farms over seven consecutive cropping seasons (long rains 2013 to long rains 2016) in Sidindi, western Kenya.

Parameter	Estimate (t ha^{-1})	SE	*P* value
NPK (intercept)	5.4	0.50	<0.05
Control	-2.7	0.50	<0.05
PK	-2.3	0.35	<0.05
NK	-0.9	0.34	<0.05
NP	-0.5	0.36	ns
Season number × NPK	-0.1	0.05	ns
Season number × Control	-0.1	0.07	<0.05
Season number × PK	-0.1	0.07	ns
Season number × NK	-0.2	0.07	<0.05
Season number × NP	-0.1	0.07	ns

3.3.4 Key factors driving variability in maize yield response to nutrient additions

A classification and regression tree was used to identify the key field level factor driving variability in normalized treatment maize grain yield (Fig. 3.1). Deviations from average yield conditions (normalized yield value of 1) represent a measure of the effect of model parameters on yield response: values greater than 1 indicate a better than average yield response, values less than 1 indicate a smaller than average response. Past animal manure application was the first splitting criterion for differences in normalized yields (Fig. 3.1), indicating that this was the key factor driving differences in maize yield response between fields. On average, where fields had past manure application, yield response was 10% greater than the average response, while for fields without past manure application, yield response was 33% less than the average response for all fields (Fig. 3.1). Thus, observed yields for fields with past manure application were up to 43% larger, indicating strong effects of past manure application on maize yield response to applied nutrients. The right hand branch of the regression tree shows that improved yield response for fields with past manure application was further related to soil texture and distance from the homestead. The largest yield responses was associated with fields with past manure application where clay and silt contents were >=24% but <35%. In the left hand branch the smallest yield responses were observed for fields without past manure application and clay and silt contents >=41% (Fig. 3.1). Fields with past manure application that were closer than 15 m from the homestead also showed a stronger yield response than those further from the homestead (Fig. 3.1).

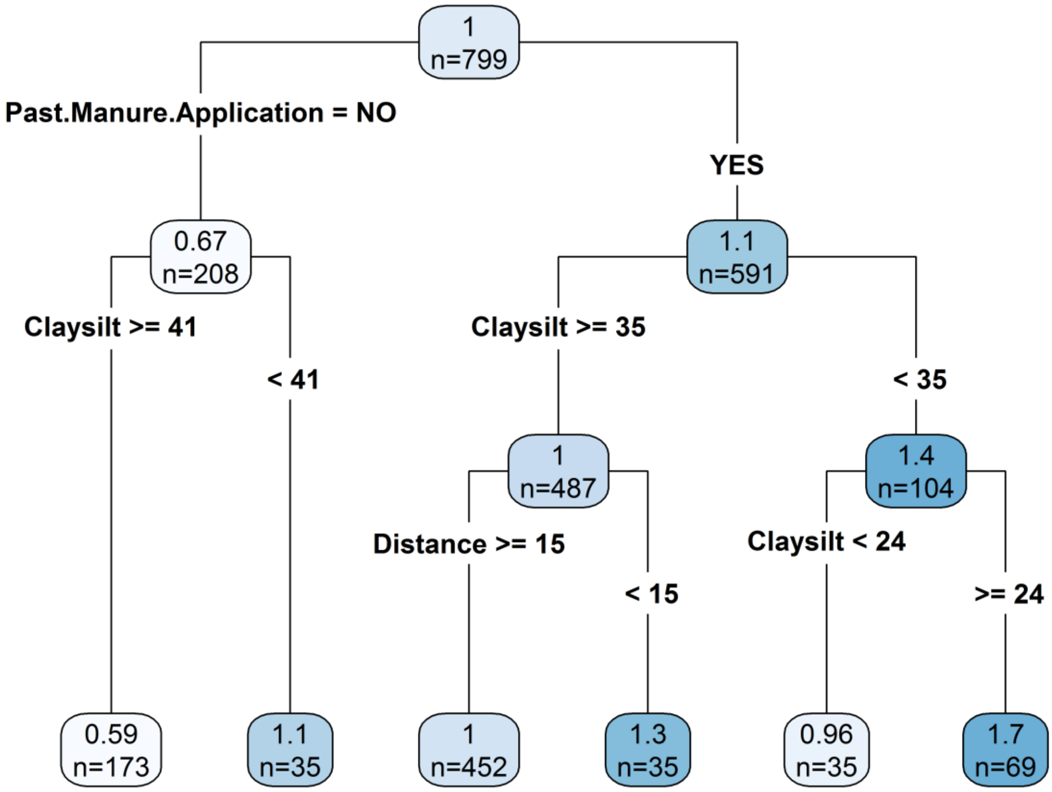

Fig. 3.1: Classification and regression tree model describing variability in normalized maize grain yield as a function of field characteristics and past management. The first value in each node indicates the average normalized yield for the specific category.

3.3.5 Effect of past manure application on yield response to applied nutrients

The improved mixed effects model with past manure application as an additional fixed effect explained more of the observed variation in yield compared to the initial model with only season number and treatment as fixed effects. This was indicated by a lower AIC value of 2331 for the improved model compared to a value of 2342 for the initial model. Model comparison also indicated that addition of past manure application significantly ($P<0.05$) improved the initial model, while addition of other field level factors did not significantly improve the model (not shown). Past manure application resulted in significantly ($P<0.05$) higher mean grain yield across all treatments except the PK treatment (Table 3.3). The largest yield increase was observed for the NK treatment where yields were higher by 2.9 t ha^{-1} in fields with past manure application. Yield increases for the control, PK, NP and NPK treatments were 1.4, 0.5, 2.0 and 0.9 t ha^{-1}. Combined application of NPK resulted in significantly ($P<0.05$) higher yield compared to all other treatments where fields had no past manure application (Table 3.3). However, where fields received past manure application, mean yield in the NPK treatment was not significantly different from that in the NP treatment (Table 3.3). Differences in yield response to N, P and K based on past manure application history were also observed. Where fields had no past manure application, yield responses calculated as the difference in yield between the NPK treatment, and treatments with N, P and K omitted were 2.3, 3.0 and 1.6 t ha^{-1} respectively. Where fields had received manure in the past, yield response to N increased to 2.7 t ha^{-1}, while that for P and K declined to 2 and 0.5 t ha^{-1} respectively. Thus effects of past manure application on yield were strongest where P and K were omitted.

Table 3.3: Pairwise comparison of mean seven season's treatment maize grain yield (t ha^{-1}) at 88% dry matter in nutrient omission trials for fields with and without past animal manure application in Sidindi, western Kenya.

Past manure application	Treatment				
	Control	PK	NK	NP	NPK
-manure	1.0^{a}	2.2^{bc}	1.5^{ab}	2.9^{c}	4.5^{d}
+manure	2.4^{a}	2.7^{a}	4.4^{b}	4.9^{bc}	5.4^{c}
P-value	<0.05	ns	<0.05	<0.05	<0.05

Mean treatment values within past manure application categories followed by a different superscript are significantly different at P<0.05)
ns = indicates no significant difference in mean yield within a treatment based on past manure application history at P<0.05)

3.3.6 Influence of past manure application on yield components

Assessment of the influence of past manure application on plant density at harvest, and the proportion of plants bearing mature cobs at harvest provided an indication of the possible mechanisms through which past manure application enhanced yields response to N, P and K (Fig. 3.2). For all treatments, fields with past manure application showed the least deviation from expected values of plant density as compared to fields without past manure application (Figs. 3.2a & 3.2b). For fields without past manure application, plant density declined over time across all treatments with some season to season fluctuations (Fig. 3.2a). The decline was strongest for the NK and NP treatments where beyond the second season, mean plant density in these treatments was always close to or below 40,000 plants ha^{-1} (Fig. 3.2a). In contrast, for nutrient additions in fields with past manure application, mean plant density was never <40,000 plants ha^{-1} in any of the seasons (Fig. 3.2b).

Mean cob to plant ratios diverged strongly among treatments over time for fields without past manure applications, while deviations were less strong for fields with past manure application (Figs. 3.2c & 3.2d). For example, in the NK treatment for fields without past manure application, about 40 % of the harvested plants did not bear a mature cob starting from the third cropping season (Fig. 3.2c). This was in contrast to in fields with past manure application where for the same treatment, harvested plants without mature cobs were never more than 25 per cent of total harvested plants in any of the seasons (Fig. 3.2d).

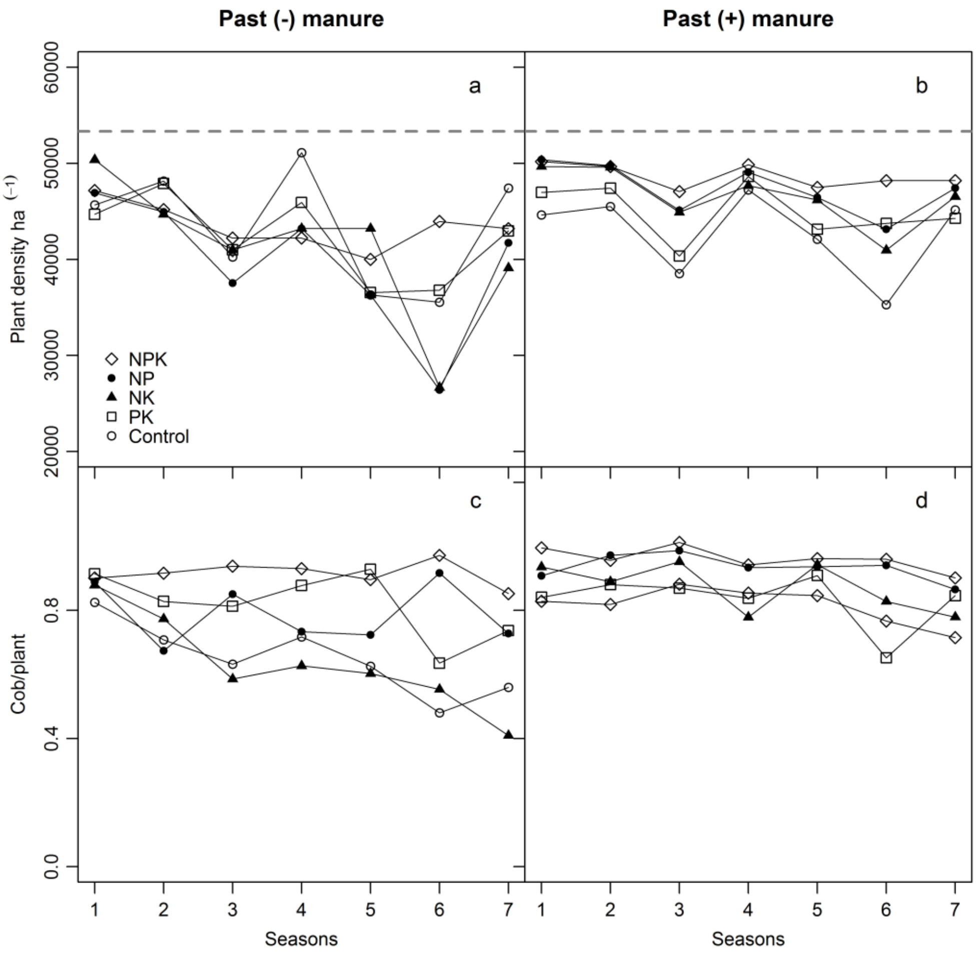

Fig. 3.2: Seasonal trends in treatment plant density ha-1 and cob/plant ratios for fields with and without past animal manure application. Seasons 1-7 refer to LR 2013, SR 2013, LR 2014, SR 2014, LR 2015, SR 2015 and LR 2016 respectively. Dotted horizontal lines represent the intended plant density at sowing (53,333 plants ha^{-1}).

3.3.7 Influence of past manure application on long term maize productivity

Cumulative maize grain yields over the seven seasons demonstrated clear effects of past manure application on maize yield productivity (Fig. 3.3). Cumulative maize grain yield was largest in the NPK treatment in fields with past manure application, with 50% of fields in this category showing cumulative yields of about 40 t ha^{-1} (Fig. 3.3). Significantly larger cumulative grain yields were observed for fields with past manure application compared with those without for all treatments with N applied, and for the control treatment (Fig. 3.3). Where NP was applied in fields with past manure application, cumulative yields were not significantly different from those observed for the combined NPK treatment irrespective of past manure application history (Fig. 3.3). Similarly, in the PK treatment, cumulative yields for fields without past manure application were not different to those observed in the no input control treatment for fields with past manure application (Fig. 3.3). This indicates that where no nutrients were applied, soil supplies of P and K for fields with past manure application matched the P and K supplied by fertilizer in the fields without past manure application. For fields without past manure application, variability in cumulative maize grain yield was largest in the NP treatment and least in the PK treatment, while for fields with past manure application, variability was largest in the NK treatment and least in the NPK treatment (Fig. 3.3).

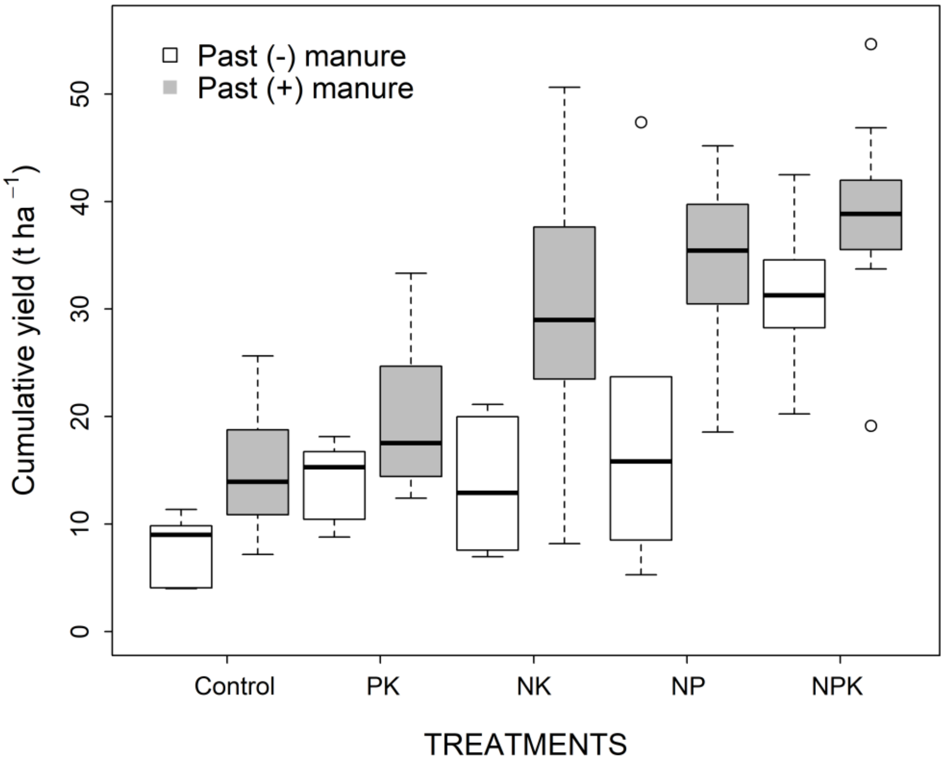

Fig. 3.3: Box plots showing variability in cumulative maize grain yield (t ha^{-1} at 88% DM) over seven seasons for fields with and without past animal manure application history in Sidindi, western Kenya. Horizontal lines within the box plots represent the median while lower and upper box plot boundaries represent the 25th and 75th percentiles respectively. Lower and upper whiskers represent the minimum and maximum values respectively, while dots above and below whiskers represent outliers.

3.3.8 Effect of past manure applications on nutrient uptake and nutrient use efficiency

Total plant nutrient uptake was influenced both by treatments imposed and by past manure application, with greater nutrient uptake observed for fields with past manure application across all treatments (Table 3.4). Total N uptake was largest in the NPK treatment in fields with past manure application, and least in the control treatment in fields without past manure application at 84.4 and 12.2 kg N ha^{-1} respectively. In fields without past manure application, total N uptake was significantly ($P<0.05$) greater for treatments with both N and P (Table 3.4). In fields with past manure application, N uptake in all treatments receiving N was significantly larger than that in the control and PK treatments. Mean N uptake was higher in fields with past manure application, with significantly ($P<0.05$) greater uptake observed in the NK and NP treatments (Table 3.4).

Small differences in N uptake in the control and PK treatments where N was not applied reflected the minimal contribution of N from past manure application.

P uptake was largest in the NPK treatment and smallest in the control treatment regardless of manure use in the past (Table 3.4). Further, plots where P was applied in combination with N showed significantly ($P<0.05$) greater P uptake compared to plots which received no N. Significantly ($P<0.05$) greater P uptake was observed in the NK, NP, and NPK treatments in fields with past manure application, likely indicative of additional P supply, and enhanced recovery of fertilizer P in fields that had past manure application.

Similar to N and P, K uptake was largest in the NPK treatments for fields with or without past manure application (Table 3.4). For fields without past manure application, the control treatment had only a significantly ($P<0.05$) smaller K uptake compared to the NPK treatment, while differences in K uptake between PK, NK, NP and NPK treatments were not significant. For fields with past manure application, significantly ($P<0.05$) more total K uptake was observed in the NK, NP and NPK treatments than in the control treatment. Treatments with N applied showed significantly ($P<0.05$) larger K uptake in fields with past manure application than the control and PK treatments. The observed larger K uptake for the NP treatments compared to the NP and NPK treatment in fields without past manure application illustrates the enhanced soil K supply in fields with past manure applications.

With mean estimated yield in the NPK treatment at 5400 and 4500 kg ha^{-1} (88 % DM) (Table 3.3), and estimated N uptake at 84.4 and 64.4 kg N ha^{-1} in fields with and without past manure applications respectively (Table 3.4), N physiological efficiency (PhEN) of dry matter production was 56.3 and 61.5 kg kg^{-1} in fields with and without past manure applications respectively. Similarly, P physiological efficiency (PhEP) was 484.9 and 707.1 kg kg^{-1}, while K physiological efficiency (PhEK) was 71.5 and 113.8 kg kg^{-1} respectively in fields with and without past manure applications.

Table 3.4: Pairwise comparison of mean treatment total nutrient uptake (kg ha^{-1} season^{-1}) for fields with and without past animal manure application in the seventh cropping season of nutrient omission trials conducted on 23 farms over seven consecutive cropping seasons (long rains 2013 to long rains 2016) in Sidindi, western Kenya.

Nutrient uptake (kg ha^{-1} season^{-1})	Past manure application	Treatment				
		Control	PK	NK	NP	NPK
N	-manure	12.2^{a}	19.7^{a}	20.4^{a}	45.7^{b}	64.4^{b}
	+manure	21.6^{a}	30.0^{a}	58.0^{b}	77.9^{c}	84.4^{c}
	P value	ns	ns	<0.05	<0.05	ns
P	-manure	1.0^{a}	3.2^{ab}	1.3^{a}	4.0^{bc}	5.6^{c}
	+manure	2.9^{a}	5.7^{b}	5.7^{b}	8.5^{c}	9.8^{c}
	P value	ns	ns	<0.05	<0.05	<0.05
K	-manure	5.6^{a}	17.6^{ab}	12.0^{ab}	14.5^{ab}	34.8^{b}
	+manure	17.0^{a}	33.0^{ab}	64.7^{cb}	48.0^{b}	66.5^{c}
	P value	ns	ns	<0.05	<0.05	<0.05

Nutrient uptake values in the same row or column within one variable followed by a different superscript are significantly different at P<0.05)
ns = indicates no significant difference in mean nutrient uptake within a treatment based on past manure application history at P<0.05)

3.3.9 Effect of nutrient application and past manure applications on soil nutrient stocks

Differences in mean soil chemical properties were mainly influenced by treatments imposed (Table 3.5). However, for all parameters assessed, mean values were larger for fields with past manure application. Significantly (*P<0.05*) larger Olsen-P and soil exchangeable K concentrations were observed for treatments with P and K applied respectively in both past manure application categories (Table 3.5). Mean soil K values in the control and PK treatments were however significantly greater in fields with past manure application (Table 3.5). For both manure application categories, mean pH values in all treatments with N applied were <5.5 (Table 3.5), indicating possible acidification following continuous application of urea in these plots. The smaller soil organic carbon contents observed for fields without past manure applications, coupled with the lack of significant differences in soil carbon stocks among fertilizer treatments, are indicative of both the contribution of long-term manure application to soil carbon stocks, and the slow turnover of soil organic matter. Past manure application resulted in up to 6.6 and 6.0 kg P ha^{-1} extra soil P in the top soil layer in the control and NK treatments which received no fertilizer P inputs (Table 3.5). Similarly, past application of manure resulted in 176 and 94 extra kg K ha^{-1} in the top soil layer in the control and NP treatments which received no fertilizer K inputs.

Table 3.5: Pairwise comparison of mixed model mean estimated treatment soil properties, and estimated soil P and K contents in the plough layer (0 – 20 cm), for fields with and without past animal manure application in the seventh cropping season of nutrient omission trials conducted on 23 farms over seven consecutive cropping seasons (long rains 2013 to long rains 2016) in Sidindi, western Kenya.

Parameter	Past manure application	Treatment				
		Control	PK	NK	NP	NPK
SOC (g kg^{-1})	-manure	10.7	10.5	10.5	10.7	10.7
	+manure	13.1	12.8	13.2	13.0	12.6
	P value	ns	ns	ns	ns	ns
pH (H_2O)	-manure	5.4^{a}	5.5^{a}	5.0^{b}	5.2^{ba}	5.2^{ba}
	+manure	5.8^{a}	5.7^{a}	5.4^{b}	5.3^{b}	5.3^{b}
	P value	ns	ns	ns	ns	ns
Olsen P (mg kg^{-1})	-manure	2.2^{a}	7.2^{b}	2.2^{a}	7.2^{b}	6.5^{b}
	+manure	4.4^{a}	10.4^{b}	4.2^{a}	7.6^{c}	7.1^{c}
	P value	ns	ns	ns	ns	ns
Soil P in plough layer (kg ha^{-1})	-manure	6.6	21.6	6.6	21.6	19.5
	+manure	13.2	31.2	12.6	22.8	21.3
	D*	6.6	9.6	6.0	1.2	1.8
Exch. K (cmol kg^{-1})	-manure	0.13^{a}	0.25^{ab}	0.27^{b}	0.12^{c}	0.17^{ab}
	+manure	0.28^{a}	0.39^{b}	0.40^{b}	0.20^{c}	0.25^{ca}
	P value	<0.05	<0.05	ns	ns	ns
Soil K in plough layer (kg ha^{-1})	-manure	152.1	292.5	315.9	140.4	198.9
	+manure	327.6	456.3	468.0	234.0	292.5
	D	175.5	163.8	152.1	93.6	93.6

Soil parameter values in the same row followed by a different superscript are significantly different at P<0.05)
ns = indicates no significant difference in mean soil properties within a treatment based on past manure application history at P<0.05)
**Indicates extra P and K content in the top plough layer in fields with past manure application*

Based on the QUEFTS model, accounting for past manure application resulted in an estimated increase in potential soil N supply by 17.3, 14.2, 18.2, 10.8 and 11.4 kg ha^{-1} at the start of the seventh season for the control, PK, NK, NP and NPK treatments respectively (Table 3.6). Differences in treatment potential soil P supply based on past manure application were largest in the NK treatment (3 kg ha^{-1}) and smallest in the NP treatment (1.1 kg ha^{-1}) (Table 3.6). In the NP treatment, past manure application resulted in an increase in potential soil K supply of 15.8 kg K ha^{-1} (Table 3.6). Further calculations based on the QUEFTS model indicated that the where N, P and K were omitted, the extra soil supply of N, P and K for fields with past manure application was equivalent to fertilizer applications of 28.3, 29.8, and 31.5 kg ha^{-1} respectively (Table 3.6).

Table 3.6: QUEFTS derived treatment potential soil nutrient supply and fertilizer nutrient equivalents for fields with and without past animal manure application in the seventh cropping season of nutrient omission trials conducted on 23 farms over seven consecutive cropping seasons (long rains 2013 to long rains 2016) in Sidindi, western Kenya.

QUEFTS Estimates	Past manure application	Treatment				
		Control	PK	NK	NP	NPK
SN (kg ha^{-1})	-manure	44.2	44.6	35.7	40.0	40.0
	+manure	61.5	58.8	53.9	50.8	51.4
	D*	17.3	14.2	18.2	10.8	11.4
Fertilizer N equivalent (kg ha^{-1})		34.5	28.3	36.3	21.6	22.8
SP (kg ha^{-1})	-manure	4.2	6.8	2.9	6.1	5.8
	+manure	6.6	9.5	5.9	7.2	7.2
	D	2.4	2.7	3.0	1.1	1.4
Fertilizer P equivalent (kg ha^{-1})		24.1	26.8	29.8	11.0	13.5
SK (kg ha^{-1})	-manure	45.8	84.4	103.5	43.5	60.9
	+manure	76.6	110.4	115.6	59.3	74.3
	D	30.8	26.0	12.1	15.8	13.4
Fertilizer K equivalent (kg ha^{-1})		61.5	52.0	24.2	31.5	26.8

**Indicates differences in potential soil nutrient supply for with and without past manure application*
SN, SP and SK refer to potential soil N, P and K supply respectively

3.4 Discussion

The application of animal manure in the past was identified as the most important factor to explain the large differences in yield and yield response to applied fertilizers between farms. Fields with past animal manure application had significantly greater yields in all treatments except PK when compared with fields without, with mean differences of 1.4, 0.5, 2.9, 2.0 and 0.9 t grain ha^{-1} per season for the control, PK, NK, NP and NPK treatments respectively. The strongly declining yield responses to unbalanced applications of N, P and K (i.e. PK, NK and NP treatments) was linked to exhaustion of the limited soil supply of P and K in fields without past manure application. These declining yields were amplified at lower soil K supply levels by strongly declining plant survival rates in response to K limitations (Wang *et al.*, 2013) and a lower proportion of plants without cobs at harvest in response to P limitations, as also observed by (Robert and Okalebo, 1992).

At both the onset and end of the trial period, fields with past manure application showed higher contents of exchangeable P and exchangeable K, equivalent to 29.8 kg P ha^{-1} and 31.5 kg K ha^{-1} of fertilizer respectively. The observed total nutrient uptake values in the NPK treatment of 84.4, 9.8 and 66.5 kg ha^{-1} for N, P and K respectively in fields with past manure application were comparable to those reported by Smaling and Janssen (1993). The applied 150, 40 and 60 kg N, P and K ha^{-1} (per season) in the NPK treatment resulted in nutrient uptake values of 64.4, 5.6 and 34.8 kg ha^{-1} in fields without past manure. Resulting fertilizer recovery rates in fields without past manure application were approximately 0.4, 0.1 and 0.5. These recovery rates for P and K correspond with commonly observed values (Smaling and Janssen, 1993), but the recovery rate for N is slightly smaller than the often observed value of 0.5 (Smaling and Janssen, 1993). The up to 20 kg ha^{-1} extra N uptake observed in the NPK treatment in fields with past manure application can therefore be attributed to an enhanced recovery of applied fertilizer N in fields with past manure application. This is corroborated by similar N uptake values observed in the PK treatment regardless of manure application history. In this treatment, plant numbers and proportion of plants without mature cobs were not different for the two past manure application categories, indicating that these lost plants did not remove a significant amount of nutrients. Indeed, past animal manure application has been related to increased fertilizer use efficiency (Castellanos-Navarrete *et al.*, 2015). In addition, the higher PhE values observed in the NPK treatment in fields without past manure application compared to fields with past manure application are indicative of both decreased and imbalanced nutrient supply (Janssen, 2011). Thus, good yields with increased fertilizer rates are very well possible in fields without past manure application, but only when N, P and K are supplied in balanced proportions. The large differences in yields under NPK fertilization, responding to differences in soil nutrient supply indicated that fertilizer application rates were not approaching maximum yields and crops were still responsive.

Our results clearly show that past manure application strongly affected yield response to fertilizer P. This was related to increased soil P supply and plant P uptake in fields with past manure application. The higher soil P supply in fields with past manure application could be as a result of less transfer of P from the labile to the stable P pools (Janssen *et al.*, 1987; Wolf *et al.*, 1987), and the less strong P fixation due to higher organic matter contents (Bationo *et al.*, 2007) as manure is the principal source of organic inputs in the western Kenya region (Castellanos-Navarrete *et al.*, 2015; Tittonell *et al.*, 2010b). This is of significance given that distinct yield response clusters observed in this study area were largely characterized by differences in yield response to P application over space and time (Njoroge *et al.*, 2017b). Spatial-temporal variations in yield response to fertilizer application in this region can therefore be largely related to differences in past field management including the application of manure. The presence of a stable P pool in tropical soils with low relative transfer rates from and to the labile pool (Sanchez, 2018) explains both the soil P resilience and the low P recovery rates, especially when the stable pool is large. This is typical of Acrisols and Ferralsols which are predominant in the western Kenya region (KARI, 1994) due to their large amounts of sesquioxides (Kruse *et al.*, 2015; Sanchez, 2018). The large variability in cumulative maize grain yields in the NK treatment in fields with past manure application, points to varied contribution of past manure application to yield response to P between farms. This is likely due to the large variability in the nutrient content of applied manure, and in the frequency and timing of manure application observed in smallholder farming systems of SSA (Rufino *et al.*, 2006; Rufino *et al.*, 2007)

Previous fertilizer recommendations in the study area based on experiments conducted in only three sites over two cropping seasons, assumed that the soils contain sufficient K reserves (KARI, 1994). A more detailed study reported that a large proportion of the farms had soils deficient in K, calcium (Ca), and zinc (Zn), as well as N and P (NAAIAP, 2014). The high incidence of K deficient fields reported can be linked to years of continuous cultivation without application of fertilizer K or manure. A common practice in majority of farms in the western Kenya region is near complete removal of stover after harvest for use as animal feed (Castellanos-Navarrete *et al.*, 2015). Stover contains large amounts of K and therefore feeding stover to animals likely results in redistribution of K within farms and landscapes. Indeed, our results showed that fields without past manure application had a significant yield response to K application. Where fields had past manure application, seasonal and cumulative yields in the NP treatment did not differ from those observed in the NPK treatment irrespective of past manure application history. Further, assessment of soil nutrient contents in the top soil layer indicated that where no nutrients were applied, fields with past manure application had up to 175.5 kg ha^{-1} more available K than fields without. In the absence of manure application, the supply of fertilizer K is therefore critical for enhancing crop productivity.

Although recommendations for maize production in the study area have recently been revised to include; the application of K fertilizers, the application of 7 t ha^{-1} of animal manure, and the additional application of secondary and micro nutrients where deficiencies are observed (NAAIAP, 2014), farmers still predominantly apply only DAP and CAN which only provide N and P. This is mainly related to the cost and lack of availability of MOP the key straight source of fertilizer K. The seasonal application of 7 t ha^{-1} of animal manure is also impractical for most farmers due to the limited quantity of manure available in most farms. Indeed, a detailed study on the management of on-farm available manure by Tittonell *et al.* (2010b) showed that at best, a majority of farms in the region are only able to produce about 2.5 t ha^{-1} DM of manure annually. A more cost-effective option would involve the additional application of secondary and micronutrients only where deficiency conditions are severe, while K fertilizer application rates can be adjusted based on past application and or availability of animal manure. Indeed, results from our study indicate that for most farms, the balanced application of NPK would suffice to sustain good yields. Given the relatively low mobility of K in the soil, it is expected that a large fraction of applied K remains on-farm and farmers can reduce required fertilizer K applications once soil stocks have sufficiently recovered.

To understand the variability of yield responses to fertilizer treatments, we evaluated soil characteristics, field characteristics, and past field management factors that affect soil fertility. Results from our study indicate that accounting for only past manure application significantly reduces the large uncertainty associated with fertilizer use within smallholder farming systems of western Kenya and provides a means to differentiate recommendations on-farm. Further, the proportion of plants with cobs at harvest and plant survival rates provide cheap indicators to monitor soil fertility and depletion of soil P and K stocks.

The observed large effects of past manure application on yields and its relatively small effect on soil fertility indicators such as SOC, and plant available P and K illustrates that this factor alone captures a significant proportion of variation in control yields. Hence, it may mask otherwise significant differences between treatments. Including past animal manure application as a co-variate in analysis of large yield response datasets is therefore strongly recommended. Especially in big data analysis approaches, an increasingly popular yet very challenging exercise within the agricultural context (Zhang *et al.*, 2015), as poor responses to fertilizer are often found in pooled experimental data.

3.5 Conclusions

Past manure application was identified as the key driver of variability in soil fertility and maize yield response to fertilizer application in smallholder farming systems of western Kenya. This was mainly related to enhanced soil P and K supply, and larger recovery of applied N in fields which received manure in the past. Poor yields and small responses to NP and NK fertilizer applications were directly linked to limited resilience of soil P and K pools in fields without animal manure application in the past. Past manure application provided a fertilizer equivalent value of 28.3, 29.8 and 31.5 kg N, P and K respectively after 7 seasons. Exhausted soil K pools in fields without manure application in the past resulted in strongly reduced plant survival rates, whereas exhausted soil P pools resulted in much lower proportions of plants with cobs. Fertilizing with NPK provided consistently good and stable yields across all fields.

Our findings highlight the need to replenish K nutrient stocks in western Kenya, in particular in fields under continuous cultivation which have not received K fertilizer or livestock manure. We recommend an assessment of animal manure application in the past as a first step towards improved fertilizer use recommendations for smallholder farmers.

3.6 Acknowledgement

This study was facilitated through funding from Agrium to the International Plant Nutrition Institute (IPNI), for research on 4R Nutrient Stewardship in western Kenya. Joost van Heerwaarden is acknowledged for assistance with statistical analysis.

Chapter 4

Improving maize yield response predictions to fertilizer applications in the QUEFTS model

This chapter will be submitted in refined form as:

Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S. Improving maize yield response predictions to fertilizer applications in the QUEFTS model

Abstract

Poor prediction of crop yield responses to fertilizer application in smallholder farming systems of sub-Saharan Africa (SSA) poses a challenge to crop productivity intensification efforts. Tools that accurately predict yield responses to fertilizers are required for improved targeting of fertilizer applications at the farm level. We assessed the accuracy of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model in predicting expected maize (*Zea mays L.*) grain yield responses to balanced and imbalanced fertilizer applications under variable soil fertility conditions in western Kenya. We used data from the seventh consecutive season of nutrient omission trials conducted on 23 farms covering the period 2013–2016, without changing treatments or plot location. Treatments included a control and PK, NK, NP and NPK. Maize grain yields and, grain and stover nutrient concentrations were significantly influenced by treatments imposed. The QUEFTS model with default parameters poorly predicted maize grain yield response to balanced and imbalanced fertilization. Calibrated fertilizer N, P and K recovery rates were 0.35, 0.11 and 0.25, compared to default values of 0.5, 0.1, and 0.5. Lower recovery rates were linked to effects of rainfall variability on maize yields, and depletion of nutrient stocks in treatments with nutrients omitted. Recalibration of parameter values in QUEFTS did improve yield response predictions. Inadequate yield response predictions in QUEFTS were linked to poor estimation of soil N, P and K supply with current relationships based on soil chemical data. Modified relationships using maize gran yields in unfertilized control treatment plots to estimate soil N, P and K resulted in substantial improvements in QUEFTS predictions. We conclude that plant-based approaches offer a promising alternative for improved estimation of soil nutrient supply for tailored recommendations, while QUEFTS should only be used at regional level, averaging out errors in soil supply estimates for N, P and K.

Key words: Soil nutrient supply, maximum accumulation, nutrient recovery, sub-Saharan Africa

4.1 Introduction

Large variability in crop yield response to application of commercially available fertilizer at the farm and field scale in smallholder cropping systems of sub-Saharan Africa (SSA) is well known (Vanlauwe *et al.*, 2006; Kihara *et al.*, 2016; Njoroge *et al.*, 2017b), and can be explained by unbalanced nutrient application (Njoroge *et al.*, 2019). Accurate tools for predicting yield responses to fertilizer applications are however lacking. Farmers are therefore frequently uncertain of the yield response to expect following fertilizer application on their farms. Such uncertainty increases the risk associated with fertilizer use (Morris *et al.*, 2007), and has been linked to the poor adoption of increased fertilizer rates within smallholder farms of SSA (Marenya and Barrett, 2009; Xu *et al.*, 2009). Reliable estimates of the expected yield response to fertilizer application within and across farms are required to improve targeting of fertilizer application at the farm level.

Soil analysis is considered as the best available approach for making fertilizer recommendations (Fryer *et al.*, 2019). Correlation and calibration processes are used to interpret measured soil nutrient availability indices (Hergert *et al.*, 1997), to identify critical levels of a particular nutrient below which crop yield response to nutrient application is expected, and above which a yield response is not expected (Voss, 1998), and to relate soil nutrient contents to plant available amounts. Fertilizer recommendations for P and K are either based on a soil balance approach, focussing on build-up and maintenance of soil stocks (Voss, 1998), or on concepts of "fertilizing the crop", where fertilizer provides nutrients not supplied by the soil (Olson *et al.*, 1987). Such approaches imply that yield response to a particular nutrient is solely based on the availability of that nutrient, and that potential nutrient supply from the soil matches actual uptake. Yield response to nutrient application is however based on the interaction between various growth factors (de Wit, 1992). This led to the development of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS), a relatively simple static model that estimates yield response to NPK fertilization in relation to soil fertility (Janssen *et al.*, 1990). Based partly on empirical, and partly on theoretical relationships, QUEFTS assumes that N, P and K are the only growth-limiting factors (Janssen *et al.*, 1990). QUEFTS further makes a distinction between the potential supply and the actual uptake of a nutrient, and additionally considers the relationship between nutrient uptake and yield (Janssen *et al.*, 1990). Initially developed for maize, QUEFTS was successfully calibrated for other crops such as rice (Haefele and Wopereis, 2005), wheat (Pathak *et al.*, 2003), cassava (Ezui *et al.*, 2017), and soybean (Yang *et al.*, 2017) in various regions of the world.

A key step in the QUEFTS model is the assessment of the potential soil supply of N, P and K based on soil organic carbon (SOC) content, available P concentrations estimated using the Olsen extraction method, and exchangeable K respectively (Janssen *et al.*, 1990). This step is however considered the most precarious part of QUEFTS as many local environmental factors may influence the relationship between soil chemical data and the supply of N, P and K (Sattari *et al.*, 2014), while soil nutrient availability indices explain only a portion of the variability in crop yield response to fertilization (Njoroge *et al.*, 2017b; Fryer *et al.*, 2019). For example, SOC is often a poor indicator of soil N availability (Carsky *et al.*, 1998), with contrasting relationships reported between SOC and potential N supply (Njoroge *et al.*, 2017b; Vanlauwe *et al.*, 2004). Uncertainty in soil N supply directly affects P and K uptake and yield, resulting in increased uncertainty of yield response.

Given the limited ability of soil analysis to predict expected yield response patterns described above, more easily accessible indicators of potential soil supply may provide a more cost-effective way of improving yield response predictions. Observed strong relationships between yield in control plots without fertilization and soil fertility (Vanlauwe *et al.*, 2006) and maize yield response to fertilizer applications (Ichami *et al.*, 2019) suggests that control-plot yield is indicative of potential soil nutrient supply. Given common practices of minimal or no fertilizer application in smallholder farms of SSA, actual farmer yields under current practices may be a better and more cost-effective predictor of potential soil nutrient supply when compared to soil analysis. This study therefore used data from on-farm experiments to assess the accuracy of the QUEFTS model in western Kenya. The study also explored options for improving the QUEFTS model based on yield in unfertilized control plots. Our specific objectives were to: (i) assess the accuracy of QUEFTS in predicting expected yields following balanced and imbalanced fertilization under heterogenous farm conditions of western Kenya; to (ii) identify limitations; and to (iii) evaluate options for improvements to better predict soil N, P and K supply. We hypothesized that current QUEFTS yield response predictions can be improved by fine tuning predictions of soil N, P and K supply.

4.2 Materials and methods

4.2.1 The QUEFTS model

4.2.1.1 Model description

QUEFTS calculates crop yield as a function of soil available and fertilizer N, P and K. A major assumption for yield prediction in QUEFTS is that crop growth is not limited by factors such as water availability, limited root penetration and poor crop management practices. Further, soils should be deep and well drained, with diagnostic soil properties within the range for which QUEFTS was tested: pH (H_2O) 4.5 – 7.0; organic C <70 g kg^{-1}; P-Olsen less than 30 mg kg^{-1}; exchangeable K less than 30 mmol kg^{-1} (Janssen *et al.*, 1990).

Crop yield modelling in QUEFTS comprises of four successive steps: (1) assessment of the potential soil supply of N, P and K based on chemical soil data; (2) calculation of the actual uptakes of N, P and K, as fractions of the potential supplies determined in Step 1; (3) designation of yield ranges as functions of the actual uptakes of N, P and K determined in Step 2; (4) calculation of the ultimate yield estimate by combining the three yield ranges established in Step 3. In this paper, we specifically focus on the initial relationships established in Step 1 for the assessment of the potential soil supply of N, P and K.

4.2.2 Assessment of potential supply of N, P and K in QUEFTS

The QUEFTS model uses empirical equations to estimate potential soil supplies of available N, P, and K based on soil organic carbon (SOC), Olsen-P, exchangeable K, and pH. A crucial requirement for the assessment of the potential supply of available nutrients from the soil is that all other growth factors, including the availability of other nutrients than the one under study, are at optimum level. For that assessment, the following relations are used:

$$S_N = \alpha_N f_N C_{org} \tag{3}$$

$$S_P = \alpha_P f_P C_{org} + \beta_P POlsen \tag{4}$$

$$S_K = \frac{\alpha_K f_K K_{Exch}}{\gamma_K + \beta_K C_{org}} \tag{5}$$

Where SN, SP and SK are soil supplies of crop available N, P and K respectively; α, β and γ are empirical parameters; and f_I is a pH dependency coefficient that describes the pH-dependency of soil organic matter mineralization (eq. 6), P solubility (eq. 7), and K exchangeability (eq. 8) (Janssen *et al.*, 1990).

$$f_N = 0.25(\mathrm{pH} - 3) \quad (6)$$

$$f_P = 1 - 0.5(\mathrm{pH} - 6)^2 \quad (7)$$

$$f_K = 0.625(3.4 - 0.4\mathrm{pH}) \quad (8)$$

Default parameter values used for empirical parameters were; $2 \times 2^{(19-9)/9}$ for α_N, 0.35 for α_P, 500 for α_K, 0.5 for β_P, 0.9 for β_K and 2.0 for γ_K (Sattari *et al.*, 2014).

4.2.3 Model evaluation data

4.2.3.1 Data source

Model evaluation data was derived from the seventh season of consecutive on-farm (*n=23*) nutrient omission experiments conducted in Sidindi area in Siaya County, western Kenya, at a latitude of 0.15 °N, a longitude of 34.4 °E and at about 1240 metres above sea level. Full details on the study area, characteristic and selection of the sites, and experimental design, soil and biomass sampling have previously been reported by Njoroge *et al.* (2017b) and Njoroge *et al.* (2019). In summary, the trials comprised of a set of five treatments including (i) control (no nutrients added), (ii) PK (40 kg P ha^{-1} + 60 kg K ha^{-1}), (iii) NK (150 kg N ha^{-1} + 60 kg K ha^{-1}), (iv) NP (150 kg N ha^{-1} + 40 kg P ha^{-1}), and (v) NPK (150 kg N ha^{-1} + 40 kg P ha^{-1} + 60 kg K ha^{-1}) in plots measuring 10 m by 10 m, with maize as the test crop. N was applied in three equal splits; at planting, at three weeks after emergence, and at six weeks after emergence. Full P and K requirements were applied at planting. The same treatments were established on each farm without replication i.e., one set of treatments was established on each farm. Trial plot locations and allocated treatments remained the same throughout the study period over seven seasons (long rains 2013 to long rains 2016). The LR 2016 season was however characterised by intermittent rainfall patterns from the midpoint of the growing season (data not shown). Specific details on soil and plant, sampling and analysis in the long rainy season in 2016 (LR 2016) are provided in the following subsections.

4.2.3.2 Soil sampling and biomass assessment

Soil sampling was conducted at the start of LR 2016 at plot (treatment) level prior to fertilizer applications. In each plot, soil samples were collected from four points using a ‘Y frame approach’ at 0-20 cm depth. Collected samples were subsequently placed in a bucket and mixed thoroughly before the composite sample was taken. These samples from each plot were air dried and passed through a 2 mm sieve prior to chemical analysis for properties used in the QUEFTS model.

At the end of LR 2016, maize was harvested at physiological maturity within a net plot of 2.25 m by 3 m including three centre rows in each plot, leaving at least 2 m on each side of the centre rows to minimize edge effects. Maize plants in this net plot were cut at about 5 cm above the ground, and the total number of plants recorded. Cobs were then detached from the stover, total cob numbers recorded, and total cob weight determined in the field using a digital scale accurate to 2 decimal places. A representative sample of cobs comprising of one ‘large’ and two ‘medium’ sized cobs were then selected, weighed and placed in a clearly labelled sample bag for further drying and processing. For stover, all stover material from the harvested net plot was weighed using a spring balance, and stover weight per plot recorded. Subsequently a sample of the stover was taken by selecting five representative plants. These were then cut into 5 cm pieces and well mixed before a subsample of 200 g was weighed using a digital scale, and placed in a clearly labelled sample bag for further drying and processing. Selected cob and stover samples were then air-dried to a constant weight, and weights and the mass fraction of air-dry cobs and stover in fresh material were determined and used to calculate air-dry grain and stover yield (t ha^{-1}).

4.2.3.3 Soil and biomass sample analysis

Processed soil and plant samples were analysed at the Lancrop Laboratories in the United Kingdom. Soil organic carbon was determined by Dumas combustion on a LECO Trumac CNS analyser, while available phosphorus (P) was determined with an Olsen extraction followed by colorimetric analysis. Exchangeable potassium (K) was determined using atomic absorption spectrometry using ammonium acetate as the extracting agent. Soil pH was determined in water using the pH electrode method in a 2 to 1 water solution. Grain and stover nitrogen (N) contents were determined by Dumas combustion on a LECO Trumac CNS analyser. Grain and stover phosphorus (P) and potassium (K) contents were determined by inductively coupled plasma emission spectrometer following ashing at 500 °C and digestion in a reverse Aqua Regia matrix.

4.2.3.4 Correcting for measurement errors in model evaluation data

Plot level measurement errors in biomass, and soil sampling and analysis can increase random errors in yield, nutrient uptake, and soil analysis measurements. Best Linear Unbiased Predictions (BLUPs) provide a means for removing measurement errors by providing an estimate of random effects (Robinson, 1991). To account for plot level effects in our model evaluation data, we determined BLUP estimates of maize grain yield, total nutrient uptake, SOC, pH, available P, and exchangeable K. For this, mixed effects models with grain yield, total nutrient uptake and/or soil chemical parameter as the response variable, and treatment as a fixed effect were fit using the 'lme4' package in R software (Bates *et al.*, 2015; R Core Team, 2017). Variations due to differences between fields were accounted for by including the field-identifier as a random effect in the mixed models. BLUP estimates of maize grain yield, total nutrient uptake, and selected soil chemical parameters were then computed using the 'predictmeans' package in R software (Dongwen *et al.*, 2018), and compared with measured values to evaluate model fit.

4.2.3.5 Relating control yields to potential soil nutrient supply

To quantify the relationship between maize grain yields in the control treatment plots with potential soil N, P and K supply, we first evaluated the relationship between maize grain yield in control treatment plots with total N, P and K uptake in PK, NK and NP treatment plots respectively. For this, scatterplots of control yield and N, P and K uptake in the PK, NK and NP treatment plots were constructed, and the relationship between control yields and nutrient uptake visually assessed. Visual assessment indicated a piecewise linear increase in N, P and K uptake with increasing maize grain yield in the control treatment plots, with a threshold control yield value of about 1 t ha^{-1}. Subsequently, segmented lines were used to model the relationship between control maize grain yield and nutrient uptake from the soil using the 'segmented' package in R (Muggeo, 2008). Ensuing model coefficients were then used to create equations for the relationship between yield in control treatment plots and soil N, P and K supply in the QUEFTS model.

4.3 Data and model evaluation

4.3.1 Data overview

4.3.1.1 Maize biomass yield and nutrient concentrations in plant and soil

Mean grain and stover dry matter yields were significantly ($P<0.05$) affected by the treatments (Table 4.1), Mean maize grain and stover yields were significantly ($P<0.05$) different and highest in the NPK treatment (Table 4.1). Smaller mean maize grain yields (88% dry matter) in NPK treatment plots by up to 0.7 t ha^{-1} relative to other seasons indicated effects of poor rainfall conditions on maize yields in the LR 2016 season (Annex A, Fig. A1). Mean grain N, P and K, and stover N and K concentrations significantly ($P<0.05$) differed between treatments (Table 4.1). Treatment without N and P applied showed significantly ($P<0.05$) smaller grain N and P concentrations respectively, compared to treatments with these nutrients applied (Table 4.1). Mean grain K concentrations in the NK treatment was significantly ($P<0.05$) larger than in the control, PK, NP and NPK treatment plots, while mean contents in the control and NP treatment plots were similar to mean grain K in the NPK treatment (Table 4.1). Across treatments, mean stover N and P concentrations were smaller than in grains, while mean stover K concentrations were larger than in grains (Table 4.1). Mean stover N was largest in the NK treatment, with contents significantly ($P<0.05$) larger than those in the control, PK, NP and NPK treatments (Table 4.1). Mean stover P concentrations did not differ between treatments, while the NK treatment had significantly ($P<0.05$) larger stover K contents compared to other treatment (Table 4.1).

Table 4.1: Mean maize grain and stover dry matter yield (t ha^{-1}), and nutrient concentration (%) in the seventh consecutive season of on-farm (*n* = 23) nutrient omission trials, in Sidindi, western Kenya.

Parameter	Treatment					
	Control	PK	NK	NP	NPK	LSD
Grain yield (t ha^{-1})	1.1^{d}	2.0^{c}	2.0^{c}	2.8^{b}	3.5^{a}	0.5
Stover yield (t ha^{-1})	1.2^{c}	2.2^{b}	2.6^{b}	3.8^{a}	4.2^{a}	0.8
Grain N (%)	1.17^{b}	1.0^{c}	1.54^{a}	1.56^{a}	1.52^{a}	0.09
Grain P (%)	0.16^{b}	0.2^{a}	0.17^{b}	0.2^{a}	0.2^{a}	0.02
Grain K (%)	0.3^{bc}	0.31^{b}	0.34^{a}	0.28^{c}	0.29^{bc}	0.03
Stover N (%)	0.62^{c}	0.41^{d}	1.02^{a}	0.88^{b}	0.75^{bc}	0.14
Stover P (%)	0.06^{a}	0.06^{a}	0.05^{a}	0.07^{a}	0.06^{a}	0.02
Stover K (%)	0.78^{d}	0.99^{bc}	1.51^{a}	0.81^{cd}	1.1^{b}	0.21

Values in the same row followed by a different superscript are significantly different at P<0.05)
LSD refers to least significant difference between means and applies for each row

Measured soil chemical properties were largely within the ranges for which QUEFTS was tested (Table 4.2). Across treatments, mean organic carbon contents were small (< 20 g kg^{-1}) and did not differ between treatments, even after 7 seasons (Table 4.2). Soil pH was significantly lower in treatments receiving N, compared with treatments with no N applied (Table 4.2). Mean P-Olsen values in the PK treatment were significantly (*P<0.05*) larger than in other treatment plots, with mean P-Olsen smallest in the control and NK treatment plots (Table 4.2). Exchangeable K concentrations were largest in the PK and NK treatments, with mean values in these treatments significantly (*P<0.05*) larger than in the NPK treatment, and in treatments without K applied (Table 4.2).

Table 4.2: Mean and range of QUEFTS diagnostic soil properties (0 – 20 cm), in the seventh consecutive season of on-farm (n=23) nutrient omission trials, in Sidindi, western Kenya.

Parameter	Treatment					LSD
	Control	PK	NK	NP	NPK	
OC (g kg^{-1})	12.1 (7-17)	11.9 (5-17)	12.4 (8-17)	12.1 (7-16)	12.0 (7-19)	0.6
pH_{H2O} (1:2)	5.8^{a} (5-7.6)	5.8^{a} (5-6.6)	5.5^{b} (4.7-6.6)	5.5^{b} (4.9-6.2)	5.4^{b} (4.9-6.1)	0.2
Olsen P (mg kg^{-1})	4.8^{c} (1-34)	11.6^{a} (2-43)	4.5^{c} (1-19)	8.4^{b} (4-17)	7.4^{bc} (3-14)	3.2
Exch.K (mmol kg^{-1})	2.5^{b} (1-6.8)	3.4^{a} (1.9-6.9)	3.7^{a} (1.6-7.4)	1.9^{c} (0.9-4.4)	2.3^{bc} (1.2-4.7)	0.5

Values in the same row followed by a different superscript are significantly different at P<0.05)
LSD refers to least significant difference between means and applies for each row

4.3.1.2 Relationships between nutrient application and maize grain yield

Figure 4.1 illustrates relationships between nutrient application, total nutrient uptake, and maize grain yield. Lower quadrants represent relationships between N, P and K applications and total N, P and K uptake respectively, while upper quadrants illustrate influence of nutrient uptake on maize grain yields (Fig. 4.1). Total N uptake increased strongly with fertilizer N application (Fig. 4.1), illustrating the strong contribution of fertilizer N application to N uptake. Increasing N uptake corresponded to increasing maize grain yields in an almost linear fashion, with about 20 kg N ha^{-1} uptake per ton increase in yield (Fig. 4.1). A similar pattern was observed for total P uptake, with maize yield increasing linearly with increasing P uptake, though plant P uptake was less strongly influenced by fertilizer P applications (Fig. 4.1). Increasing K uptake generally resulted in increasing maize grain yield, though effects were less pronounced (Fig. 4.1). Total K uptake patterns were, on average, not strongly influenced by fertilizer K applications, with the application of 60 kg K ha^{-1} not resulting in substantial increase in uptake compared to zero K application (Fig. 4.1). Large variations in N, P and K uptake at zero application rates (Fig. 4.1) indicated strong differences in soil nutrient supply between farms, especially for K.

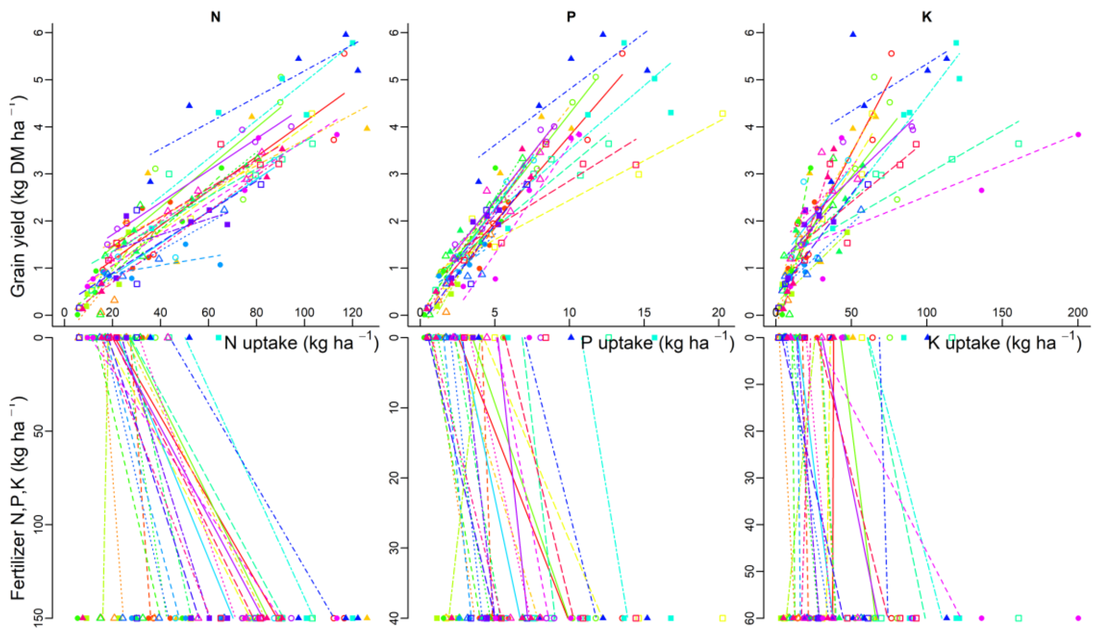

Fig. 4.1: Two quadrants diagrams with graphs for the relationship between total nutrient uptake and maize grain yield in the upper quadrants, and the relationship with fertilizer N, P and K applications on total N, P and K uptake respectively. Different symbols represent different fields.

4.3.2 Evaluation and calibration of QUEFTS

4.3.2.1 Yield prediction in the default QUEFTS model

Predicted maize grain yields with the default QUEFTS model were not in line with BLUP estimates of measured grain yield (Fig. 4.2a). QUEFTS only explained about 47% of variation in yield response to fertilization, with an RMSE of 848 (Fig. 4.2a). Predicted yield in QUEFTS is a function of both relations between nutrient uptake and yield, and relations between soil potential nutrient supply and recovery of applied nutrients, and crop uptake. Limitations in yield prediction in QUEFTS may therefore result from poor relationships between nutrient uptake and yield, or poor estimation of the supply of nutrients from the soil and from applied fertilizer. To evaluate if poor yield prediction was related to inadequate relationships between nutrient uptake and yield in the QUEFTS model, we substituted nutrient uptake from the soil as estimated by potential soil N, P an K supply relations in QUEFTS with actual measurements of N, P and K uptake in PK, NK, and NP treatment plots respectively. Improved agreement between QUEFTS predicted and BLUP estimates of measured maize grain yield demonstrated that QUEFTS captured relationships between nutrient uptake and yield well (Fig. 4.2b). This suggested that inadequacies in yield prediction in QUEFTS are more likely related to QUEFTS estimation of potential soil nutrient supply, and the recovery of fertilizer N, P and K. Observed overestimation of yields in the NP and NPK treatment plots in the modified QUEFTS model (Fig. 4.2b) suggested larger recovery of applied N in QUEFTS compared to actual recovery, indicating need for calibration of recovery values in QUEFTS. The presence of points outside boundary lines of maximum nutrient dilution and accumulation also indicated that parameters for maximum and dilution and accumulation required calibration (Annex A, Fig. A3).

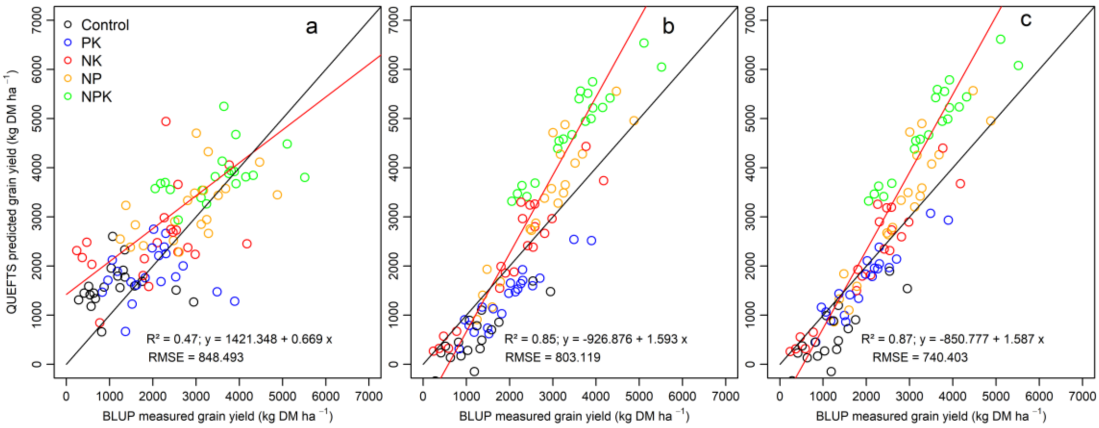

Fig. 4.2: Relationship between QUEFTS predicted and BLUP estimates of measured grain yield for: a) QUEFTS with N, P and K uptake from the soil based on QUEFTS default equations; b) QUEFTS with soil N, P and K supply based on measured total N, P and K uptake in the PK, NK and NP treatment plots respectively; and, c) QUEFTS with soil N, P and K supply based on measured total N, P and K uptake in the PK, NK and NP treatment plots respectively, with calibrated parameter values for N, P, and K maximum dilution and accumulation, and recovery rate.

4.3.2.2 Calibrated QUEFTS parameters

Recovery values for fertilizer N, P and K were estimated by calibration of QUEFTS based on yields in NPK plots only. Calibrated recovery rates were 0.35, 0.11 and 0.25 for N, P and K respectively (Table 4.2). These values were similar to recovery estimates of 0.36, 0.11 and 0.29 for N, P and K respectively based on BLUP N, P and K uptakes. The calibrated value of maximum accumulation *(a)* for N was slightly larger than the default value, while values for P and K were slightly smaller than default values (Table 4.2). The calibrated maximum dilution *(d)* value for N of 100 was substantially larger than the default value of 70. Comparatively, calibrated values of maximum P and K dilution were only marginally smaller than default values (Table 4.2).

Yield and nutrient uptake patterns with modified maximum dilution and accumulation parameter values illustrated nutrient deficiency and sufficiency patterns between treatments and fields (Fig. 4.3). Strongly N diluted conditions in control and PK treatment plots (Fig. 4.3a) illustrated strongly N deficient conditions for these treatment plots, explaining observed changes in values for maximum N dilution (Table 4.2). Treatment plots with NPK supplied indicated sufficient N availability, as N was neither diluted nor accumulating (Fig. 4.3a). Observed strong N accumulation in some fields in plots with NK and NP supplied suggested limitations in plant growth due to deficiencies of P and K respectively (Fig. 4.3a). Strongly P diluted conditions in control and NK treatment plots reflected effects of continuous cropping with no P application on P availability (Fig. 4.3b). The proximity of some points to the maximum P dilution line for the relationship between P uptake and yield in NP and NPK treatment points suggested insufficient P uptake (Fig. 4.3b). This could be related to limitations in recovery of applied fertilizer P. Maize grain yield and K uptake patterns indicated strongly K deficient conditions in control treatment plots, while K was accumulating in some NK treatment plots (Fig. 4.3c). Patterns of grain yield and total K uptake in NP treatment plots indicated that while some fields were strongly deficient of K, other fields still had substantial K stocks despite seven consecutive seasons of cropping without fertilizer K application (Fig. 4.3c).

Table 4.3: Default and calibrated parameter values of average fertilizer efficiency, physiological efficiency at maximum accumulation of nutrient *(a)*, and maximum dilution of nutrient *(d)* in the seventh consecutive season of on-farm *(n=23)* nutrient omission trials in Sidindi, western Kenya.

Parameter	Nutrient	Default values (Janssen et al., 1990)	Calibrated values
Fertilizer recovery fraction	N	0.50	0.35
	P	0.10	0.11
	K	0.50	0.25
Physiological efficiency at maximum accumulation *(a)* (kg grain kg^{-1} nutrient)	N	30	36
	P	200	188
	K	30	24
Physiological efficiency at maximum dilution *(d)* (kg grain kg^{-1} nutrient)	N	70	100
	P	600	588
	K	120	114

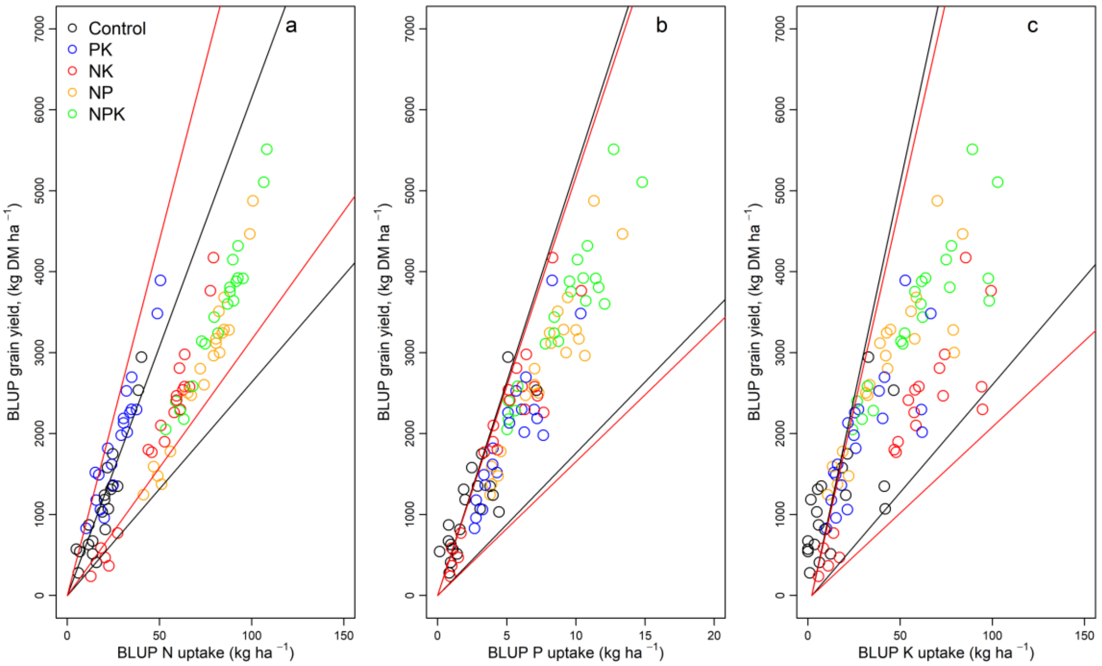

Fig. 4.3: Relationship between maize grain yield and: a) total N uptake; b) total P uptake c) total K uptake in the seventh consecutive season of on-farm nutrient omission trials (*n* = *23*) in Sidindi, western Kenya. Black and red upper and lower lines are maximum nutrient dilution and maximum nutrient accumulation lines respectively based on the default (Janssen *et al.*, 1990) and calibrated values respectively.

Calibration of parameter values for fertilizer N, P and K recovery, and maximum accumulation and dilution resulted in substantial improvements in QUEFTS estimated uptake of applied N, while improvements in estimated uptake of applied P and K were minimal (Annex A, Fig. A4). Calibration did not however improve QUEFTS yield predictions (Fig. 4.2c). Calibration results strongly suggested the need to evaluate relationships for potential soil nutrient supply in QUEFTS.

4.3.2.3 QUEFTS yield prediction with soil nutrient supply based on control yields

Potential soil N, P and K supply relations in QUEFTS imply correlation between SOC, P-Olsen and exchangeable K, and total N, P and K uptake in PK, NK and NP treatment plots. BLUP total N and P uptake were however poorly related to BLUP estimates of SOC and P-Olsen respectively, with only exchangeable K closely related to total K uptake (Annex A, Fig. A5b, A5d & A5f). This suggested poor estimation of potential soil N and P supply in the default QUEFTS model. On the contrary, grain yield in the control treatment plot was closely related to N, P and K uptake in PK, NK and NP treatment plots respectively (Annex A, Fig. A5a, A5c & A5e). Using estimated coefficients from relationships between grain yield in the control treatment plots and nutrient uptake, new relationships for estimates of soil nutrient supply in QUEFTS were used based on equations 9 – 11 below.

$$S_N = 5.001 + 0.0233Y_C;\ if\ Y_C > 1070, S_N = S_N - 0.0121Y_C \quad (9)$$

$$S_P = -1.396 + 0.0068Y_C;\ if\ Y_C > 1070, S_P = S_P - 0.0024Y_C \quad (10)$$

$$S_K = -5.905 + 0.0535Y_C;\ if\ Y_C > 1070, S_K = S_K - 0.0394Y_C \quad (11)$$

Where Y_C is grain yield in the control treatment plot.

Estimation of potential soil nutrient supply using new relations based on maize yield in control treatment plots significantly improved maize yield prediction in the QUEFTS model, explaining up to 65% of variation in yield response to fertilization (Fig. 4.4). In this figure, relationships for measured and predicted yield in NPK treatment plots offer the most legitimate evaluation points for model improvement. This is due to the expected influence of yield predictions in the PK, NK and NP treatments by the prior estimation of potential soil nutrient supply based on relationships between nutrient uptake in these treatment plots, and yield in the control treatment plots. Observed closer agreement between measured and QUEFTS predicted yield in NPK treatment plots (Fig. 4.4) however confirms the superiority of potential nutrient supply based on measured yield in unfertilized plots compared to the use of soil analysis data (Fig. 4.2a).

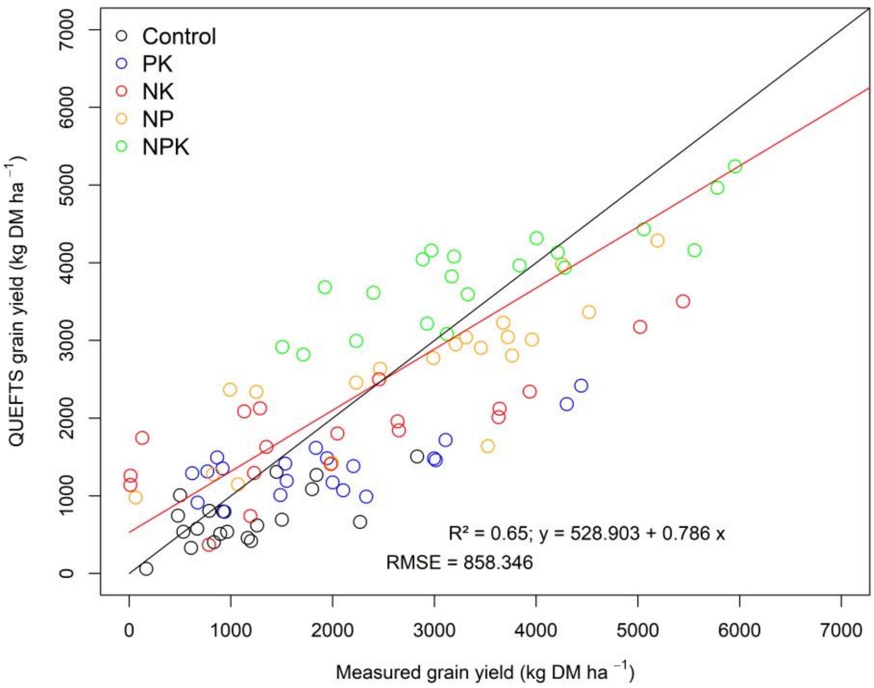

Fig. 4.4: Relationship between QUEFTS predicted and measured grain yield, with potential soil nutrient supply in the QUEFTS model based on maize grain yield in the unfertilized control treatment plot.

4.4 Discussion

A thorough understanding of maize yield responses to a variable supply of macronutrients is important to optimize recommendations to field conditions (Cassman, 1999), following the 4R principles (Johnston and Bruulsema, 2014). The QUEFTS model with default parameters (Janssen *et al.*, 1990) explained about 47% of variation in observed yields, yet with a bias and substantial errors (RMSE 848 kg ha^{-1}), and did not accurately predict maize grain yields following balanced and imbalanced fertilization under variable soil fertility conditions. We found that relationships between nutrient uptake and yield were accurate. Subsequent calibration of parameter values for recovery, and maximum accumulation and dilution of N, P and K did not improve model predictions sufficiently. Limitations in QUEFTS yield prediction were linked to poor estimation of soil nutrient supply based on current relations for soil nutrient supply. In particular measured SOC and P-Olsen were poor indicators of soil supply and crop N and P uptake. Poor relationship between soil nutrient supply and soil properties in Step 1 of QUEFTS was also reported by Smaling and Janssen (1993), Saïdou *et al.* (2003) and Shehu *et al.* (2019), with re-calibration required to improve relationships between soil properties and soil nutrient supply. Recently recalibrated relationships for soil nutrient supply for on-farm studies in Nigeria (Shehu *et al.*, 2019) did not result in better uptake estimates (not shown) for our study in western Kenya, indicating the need for site specific calibration of soil nutrient supply relations. This requirement presents a challenge for the effective use of QUEFTS for crop yield predictions and responses to fertilizer applications on individual smallholder farms.

Calibrated N and K fertilizer recovery rates were lower than default values in the QUEFTS model. Lower recovery values are expected given that NPK yields in LR 2016 were significantly lower than in other seasons by 0.7 t ha^{-1}. We know that soil supply was larger in the NPK plots than in NP for K, PK for N and NK for P. However, the apparent recovery when based on the BLUP uptake estimates was similar to the calibrated values. This suggests that calibration accounted for lower yields by lowering recovery values considering that relationships between uptake and yield were in line with default QUEFTS. A 700 kg ha^{-1} extra yield under balanced nutrition would have required an additional 14, 1.75 and 9.3 kg ha^{-1} respectively of N, P and K uptake from fertilizer. This translates to an increased recovery of 0.093 for N, 0.044 for P and 0.16 for K, resulting in an estimated recovery for normal seasons of 0.45 for N, 0.15 for P and 0.45 for K. These values are very much in line with expectations considering that fertilizer P was placed close to the planting hole (Van der Eijk *et al.*, 2006). Shehu *et al.* (2019) recently reported N, P and K recovery rates of 0.32-0.42, 0.08-0.16, and 0.37-0.54 respectively in farms in Nigeria following the application of 120-140, 40-50 and 40-50 kg ha^{-1} of fertilizer N, P and K respectively. The lower recovery rates were observed in the Sudan Savanna zone, with poor rainfall conditions that limited yields, while values in the Guinea Savanna zone were comparable to default values in QUEFTS, (Shehu *et al.*, 2019). This is in line with our observed effects of poor rainfall conditions on recovery of fertilizer N, P and K.

Apart from the previously identified need for recalibration, soil analysis based estimates of soil nutrient supply are further hampered by the inability of soil analysis to effectively capture differences in soil nutrient supply between and within farms. Previous findings showed that soil analysis was poorly reflective of strong variations in soil nutrient supply between farms (Njoroge *et al.*, 2017b; Njoroge *et al.*, 2019). Working in western Kenya, Vanlauwe *et al.* (2006) reported that soil total N explained up to 44% of the variation in maize yield response to N in one study area, with no relationship observed between soil total N and maize yield response to N in a separate study area. These contrasting effects of measured total soil N on soil N supply were linked to differences in quality of applied organic resources between sites (Vanlauwe *et al.*, 2006; Vanlauwe *et al.*, 2002), resulting in substantial differences in soil available N that were not reflected in measurements of soil total N or soil organic matter. Given the frequently documented strong variations in soil fertility at the farm level (Zingore *et al.*, 2007a; Tittonell *et al.*, 2005b), the use of soil analysis in assessment of differences in plant available soil nutrient stocks between fields remains a major challenge.

Improved QUEFTS crop yield predictions based on estimates of N, P and K supply from the soil based on unfertilized plots suggest that plants are a more accurate source of information on soil nutrient supply. A key assumption here is that nutrient contents are reasonably constant, and yield variation in unfertilized plots is determined by variation in soil nutrient supply. Yields in unfertilized control treatment plots have previously been used to interpret (Kihara *et al.*, 2015; Ronner *et al.*, 2016; Kihara and Njoroge, 2013), and explain crop yield response patterns to fertilizer applications on smallholder farms of SSA (Ichami *et al.*, 2019). Theoretical relationships between for example, crop yield with fertilizer N applications and yield in unfertilized control treatment plots have also been developed (Vanlauwe *et al.*, 2011), underscoring the utility of crop yields in unfertilized plots as an indicator of soil nutrient supply. Given that crop yield is among the key indicators of soil quality (Murage *et al.*, 2000; Kuria *et al.*, 2019) and easily assessed by farmers (Mairura *et al.*, 2007), a plant based approach to soil nutrient supply assessment appears feasible once developed relationships are tested on a broad range of fields. For example, actual farm yields are part of the diagnostic criteria for estimating soil nutrient supply and predicting expected crop yield response to fertilizer application in Nutrient Expert (NE) a fertilizer decision support tool based on initial relationships established in the QUEFTS model (Pampolino *et al.*, 2012). Improved predictions of the expected crop yield response to fertilizer application using NE has enabled farmers in major cereal cropping systems in Asia substantially increase yields and fertilizer use efficiency (Pasuquin *et al.*, 2010; Xu *et al.*, 2014; Chuan *et al.*, 2013).

By accounting for effects of interactions between N, P and K uptake on final yield, QUEFTS serves as one of the most versatile tools for refining predictions of crop yield responses to fertilizer use. QUEFTS also perfectly captures nutrient uptake and yield relationships. While relationships for soil nutrient supply remain the weak-link in QUEFTS, it is clear that modified relations that improve soil nutrient supply estimates significantly improve yield response predictions. Yields in unfertilized control treatment plots provide a means for better estimating soil N, P and K supply. Given the minimal fertilizer application rates in the majority of smallholder farms of SSA, it is expected that actual farm yields are indicative of the soil nutrient supply potential. Accurately measured crop yields under current farmer management therefore present a means for improving soil nutrient supply estimates in QUEFTS. Plant analysis followed by assessment of relationship between grain yield and nutrient uptake can be used to identify nutrient deficient conditions: by comparing N and P concentrations in grain and

K concentrations in stover with reported values in literature; or by calculated values of optimum N, P and K dilution and accumulation with values from literature (Janssen *et al.*, 1990), and this study. The use of the QUEFTS to simulate balanced nutrient uptake requirements for N, P and K across a range of potential maize yield values has further provided a means for estimating maize nutrient requirements at different yield targets for a range of environments (Setiyono *et al.*, 2010). Reported linear relationships between balanced uptake and up to 60 -70% of potential yields provide a means for estimating maize N, P and K requirements based only on potential yield and yield target in situations where N, P and K are the main limiting nutrients (Setiyono *et al.*, 2010). This indicates that while QUEFTS does not accurately capture between-field variation, it can be useful at the regional scales to provide estimates of fertilizer recommendations based on balanced nutrient uptake requirements per ton of grain (ten Berge *et al.*, 2019) and expected fertilizer recovery rates. Field level fine tuning of such recommendations can then be conducted based on local target yields, and estimates of soil nutrient supply based on past nutrient management practices and current yields based on farmer input, as currently implemented in the Nutrient Expert (Pampolino *et al.*, 2012).

4.5 Conclusions

The original QUEFTS model did not accurately predict maize grain yields following balanced and imbalanced fertilization. Limitations in yield prediction were linked to poor estimation of soil nutrient supply based on current relationships for soil nutrient supply. Calibrated values for fertilizer N and K recovery were lower than default values in QUEFTS, while recovery rate for fertilizer P was similar to the default value in QUEFTS. Lower fertilizer N and K recovery rates were linked to limitations in rainfall during the growing season, and depleted soil nutrient stocks in treatments with nutrients omitted. QUEFTS accurately captured relationships between nutrient uptake and maize yield. Modified relationships for soil nutrient supply based on yield in the unfertilized control treatment plots resulted in improved maize grain yield predictions under variable soil fertility conditions. The need to re-calibrate equations for soil nutrient supply and the inability of soil analysis to effectively capture differences in soil fertility between fields suggests that current understanding of mineralisation and soil nutrient supply is insufficient. This indicates that with current relationships for soil nutrient supply based on soil analysis data, QUEFTS is not suited for field-specific recommendations under the heterogenous soil fertility conditions typical for SSA.

We conclude that improved relationships that provide better estimates of soil nutrient supply in Step 1 of QUEFTS are required for improved predictions of expected yield response to fertilizer applications at the farm level. Plant based approaches for assessment of soil nutrient supply offer a promising option once relationships between yields in unfertilized plots and nutrient uptake are further validated. In practise, N and P fertilization will be needed for many years on strongly depleted soils while the need for K can be guesstimated from the use of animal manure (Njoroge *et al.*, 2019) and stover K concentrations. K fertilization will however be a requirement at high target yields irrespective of current soil stocks. Further, relationships between balanced N, P and K uptake and maize yield, combined with desired yield increments offer an alternative for recommendations when other factors are not limiting growth.

Chapter 5

Feed the crop, not the soil: Regenerating crop productivity on nutrient depleted soils in western Kenya.

This chapter is submitted to Agronomy Journal as:

Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S. Feed the crop, not the soil: Regenerating crop productivity on nutrient depleted soils in western Kenya.

Abstract

Soils with depleted and imbalanced nutrient stocks limit crop productivity on smallholder farms of sub-Saharan Africa (SSA). We assessed patterns of maize grain yield response and changes in soil nutrient stocks following combined fertilizer nitrogen (N), phosphorus (P) and potassium (K) applications on strongly nutrient depleted soils in the Sidindi area of western Kenya. Experiments were conducted in smallholder farmers' fields over eleven consecutive seasons covering the period 2013 – 2018. We used data from on-farm nutrient omission experiments, and balanced NPK experiments established in former nutrient omission plots. Maize yields responded strongly to balanced NPK fertilization on strongly nutrient depleted soils. Mean yields in the second season of combined NPK application on strongly depleted soils were 5.5, 6.7, 6.5 and 7.0 t ha^{-1} at 88% dry matter in the former control, PK, NK and NP treatment plots respectively, compared with 7.5 t ha^{-1} in the long-term NPK treatment plots. We conclude that strongly nutrient depleted clay rich soils such as those of western Kenya are responsive to balanced NPK applications, and no prior investments to rebuild nutrient stocks and soil organic matter are required for crop yields to be increased. Adjustments of initial yield expectations are however required in the first one to two seasons of balanced fertilization on strongly P and K depleted soils. Our results support a strategy of feeding the crop directly, rather than the approach of feeding the soil to feed the crop that is often recommended.

Key words: Responsive soils, balanced fertilization, nutrient stocks, sub-Saharan Africa

5.1 Introduction

Continuous cultivation with little or no nutrient replenishment, which is widespread in sub-Saharan Africa, leads to declines in soil organic matter contents and poor soil fertility resulting in poor crop yields (Sanchez, 2002; Kihara *et al.*, 2015). Sanchez et al. (1997) argued for the need to replenish soil fertility in Africa to address poor crop productivity yet the problem persists. Soil scientists often suggest the need to "feed the soil not the crop", which is aligned with the idea of soil fertility replenishment. Over the past 20 years, a broad consensus has emerged on the need to manage all of the scarce nutrient resources efficiently through integrated soil fertility management (Vanlauwe *et al.*, 2010). The quantities of organic manures available are generally too limited to meet crop nutrient requirements, so nutrients need to be added through fertilizers to raise productivity (Vanlauwe *et al.*, 2015).

Crop responses to commonly available fertilizers on nutrient depleted soils are highly variable and difficult to predict (Zingore *et al.*, 2007a; Vanlauwe *et al.*, 2011). This is largely linked to differences in the extent of nutrients depletion, as nutrient depletion rates depend on both differences in field management, and soil properties (Sanchez *et al.*, 1997). Improvements in the prediction of crop responses to fertilizer application in nutrient depleted soils is therefore required, as fertilizer use is a prerequisite for substantial improvements in crop productivity in SSA (Vanlauwe *et al.*, 2015).

Detailed studies on patterns of crop yield responses following fertilizer application in nutrient depleted soils in the SSA region are limited. Most of the few studies conducted have been restricted to research stations (Bationo *et al.*, 2012b), where conditions are often quite different from those on farmers' fields. Where studies have been conducted on-farm, selection of nutrient depleted fields has been based on: location of fields from the homestead (Vanlauwe *et al.*, 2006); soil texture and past management (Zingore *et al.*, 2007b); and or farmer observed declines in crop yield (Nezomba *et al.*, 2010). There is therefore a paucity of long-term yield response studies on nutrient depleted soils on smallholder farms.

On-farm nutrient omission trials conducted over multiple seasons in western Kenya (Njoroge *et al.*, 2017b) provide sites that support the assessment of nutrient response patterns in severely N, P and K depleted soils. Balanced fertilizer application in these soils offers an opportunity for the assessment of short-term patterns of changes in crop productivity and soil nutrient stocks on smallholder farms in SSA with nutrient depleted soils, and imbalances in plant available nutrients. Comparisons of experimental findings with model estimates further offers the opportunity to evaluate and improve model predictions, allowing for more refined model predictions at scale. The RC-P model which predicts crop response to fertilizer P based on recovery of applied fertilizer P, and changes in soil P pools (Wolf *et al.*, 1987), has proved successful in predicting patterns of crop P uptake to P fertilization in soils with varying P stocks (Janssen *et al.*, 1987). Given the model's minimal data requirements (Wolf *et al.*, 1987), it is suited for use in the frequently data scarce environment of SSA. Improved understanding of crop yield response to in particular fertilizer P is critical as previously observed strong spatial temporal yield responses to fertilizer N, P and K applications in the western Kenya region were mainly attributed to large differences in yield response to fertilizer P application (Njoroge *et al.*, 2017b). This study therefore aimed at improving the understanding of changes in crop productivity and soil nutrient stocks following fertilizer N, P and K application on soils subjected to long-term nutrient depletion. We hypothesized that nutrient depleted soils in western Kenya are responsive to balanced NPK applications but nutrient recovery depends on the status of soil nutrient pools. Our specific objectives were to: (i) assess patterns of crop productivity following N, P and K application on strongly N, P and/or K depleted soils; (ii) evaluate the resilience of soil nutrient stocks; (iii) assess the short-term recovery of past N, P and K applications on soils with imbalanced nutrient stock; and (iv) evaluate the capacity of the RC-P model to simulate crop P uptake in soils with imbalanced nutrient supplies.

5.2 Materials and methods

5.2.1 Study area and experiments

The study was conducted in Sidindi, western Kenya, at a latitude of 0.15 ^{o}N, a longitude of 34.4^{o}E and at about 1240 metres above sea level. Annual rainfall ranges from 1600 – 2000 mm and is distributed over two distinct seasons with a long rainy (LR) season from March to July and a short rainy (SR) season from September to December. Full details on the study area, characteristic and selection of the sites are provided by Njoroge *et al.* (2017b). The study comprised of three experimental phases conducted across the period 2013 to 2018 with maize as the test crop. In all three experiments, a short-season maize variety DK8031 was sown at the recommended spacing (75 × 25 cm) to give 53,333 plants ha^{-1} after thinning. Two seeds were sown per planting station and thinned to one plant at two weeks after emergence. All plots were weeded manually at three and six weeks after emergence. Specific details of each experimental phase are described below.

5.2.1.1 First experimental phase

The first experimental phase (Phase 1) comprised of nutrient omission trials established at the onset of the long rainy season in 2013 on 23 different farmers' fields considered representative of the study area based on socio-economic characteristics and soil conditions (Njoroge *et al.*, 2017b). This experiment ran for seven seasons (long rains 2013 to long rains 2016). In each farm, urea, triple super-phosphate (TSP) and muriate of potash (MOP) were used as N, P and K sources, respectively, to establish a set of five treatments including: (i) control (no nutrients added); (ii) PK (40 kg P ha^{-1} + 60 kg K ha^{-1}); (iii) NK (150 kg N ha^{-1} + 60 kg K ha^{-1}); (iv) NP (150 kg N ha^{-1} + 40 kg P ha^{-1}); and, (v) NPK (150 kg N ha^{-1} + 40 kg P ha^{-1} + 60 kg K ha^{-1}) in plots measuring 10 m by 10 m. The same treatments were established on each farm without replication i.e., one set of treatments was established on each farm. Trial plot locations and allocated treatments remained the same throughout the experimental period. Yield response patterns to varied fertilizer N, P, and K application in the first six cropping seasons of this experiment have been previously reported by Njoroge *et al.* (2017b).

5.2.1.2 Selection of fields for Phases 2 of the experiment

Selection of fields for the second phase (Phase 2) of the experiment was conducted at the end of the Phase 1. Out of the initial 23 fields used in Phase 1, 17 fields were available for continuation in Phase 2. Out of these 17 fields, four fields were reserved for an experiment aimed at assessment of the recovery of past applications of N, P and K with NPK omission trials (Phase 2-NOT). Selection of these four fields was based on findings from Phase 1 of the experiment that identified distinct N, P and K yield response clusters (Njoroge *et al.*, 2017b), and showed that past manure application was a key factor explaining yield response to especially P and K (Njoroge *et al.*, 2019). Subsequently, three fields without past manure applications that included: (i) two fields strongly responsive to N, P and K; and (ii) one field strongly responsive to N and P, but with moderate response to K were selected. A fourth field which had past manure application, and showed strong response to N, moderate response to P, and minimal response to K application was also included. In these four fields, a final season of nutrient omission trials established in Phase 1 was conducted in the SR 2016 season to confirm observed response patterns. The remaining thirteen fields were reserved for an experiment where all plots were fertilized with NPK (Phase 2-NPK). This experiment included eleven fields with past manure application, and two fields without past manure application.

5.2.1.3 Experimental Phase 2-NPK

Phase 2-NPK experiment was established at the onset of the short rainy season in 2016 to assess maize yield response, and changes in soil nutrient stocks following combined N, P and K application on nutrient depleted soils. For this, each of the five nutrient omission trial plots previously under control, PK, NK, NP and NPK treatments in Phase 1 were converted to full NPK treatments in the entire 10 m by 10 m plot area. This was achieved by applying nutrients previously omitted in each of the prior nutrient omission treatments, to give a total of five NPK treatment plots that differed in past nutrient application. N, P and K application rates were similar to those of the initial full NPK treatment (150 kg N ha^{-1} + 40 kg P ha^{-1} + 60 kg K ha^{-1}). The Phase 2-NPK experiment ran for four consecutive seasons (short rains 2016 to long rains 2018) without changing allocated treatments and trial plot locations. In the last cropping season, the number of fields reduced to eight following the withdrawal of some farmers from the experiment.

5.2.1.4 Experimental Phase 2-NOT

Phase 2-NOT of the experiment was established at the onset of the long rainy season in 2017 in the preselected four fields from Phase 1 of the experiment. This experiment comprised of superimposed nutrient omission trials and aimed to assess the recovery of past N, P and K applications on soils with imbalanced nutrient stocks. For this, each of the previous five nutrient-omission treatment plots were subdivided into four sub-plots each measuring 4.5 m by 4.5 m with 1 m wide paths separating individual sub-plots. In each of the sub-plots, a set of four treatments including: (i) PK (40 kg P ha^{-1} + 60 kg K ha^{-1}); (ii) NK (150 kg N ha^{-1} + 60 kg K ha^{-1}); (iii) NP (150 kg N ha^{-1} + 40 kg P ha^{-1}); and, (iv) NPK (150 kg N ha^{-1} + 40 kg P ha^{-1} + 60 kg K ha^{-1}) were established to give a total of twenty sub-plots in each field (Fig. 5.1). These trials were run for three consecutive seasons (long rains 2017 to long rains 2018) without changing allocated treatments and trial sub-plot locations.

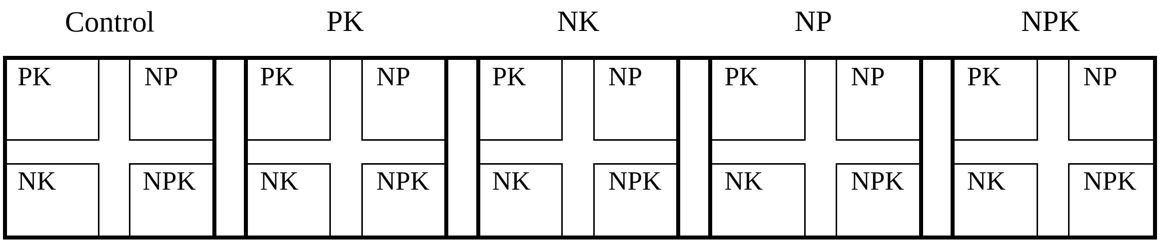

Fig. 5.1: Schematic representation of the experimental layout in Phase 2-NOT. Bold lines indicate boundaries of initial nutrient omission treatment plots in Phase 1, with the respective treatment names in bold.

5.2.2 Soil sampling

Initial soil sampling was conducted at the onset of Phase 1 with a single bulked sample from each experimental site (field) in February 2013 and reported by Njoroge *et al.* (2017b). To assess changes in soil nutrient stocks following varied nutrient application, subsequent soil sampling was conducted at plot (treatment) level. Sampling intervals were scheduled at three phases: (i) end of the third season in Phase 1 (August 2014); (ii) start of the last season in Phase 1 (February 2016); and, (iii) start of the last season of Phase 2-NPK and Phase 2-NOT (February 2018). In all instances, soil samples were collected in each plot from four points using a ‘Y frame approach’ at 0-20 cm depth. Collected samples were subsequently placed in a bucket and mixed thoroughly before the composite sample was taken. After each sampling period, soil samples were air dried and passed through a 2 mm sieve and well stored prior to chemical analysis. At the end of the study period, all samples from the three sampling periods were analysed as one batch at Lancrop Laboratories in the United Kingdom. Total nitrogen (N) and organic carbon were both determined by Dumas combustion on a LECO Trumac CNS analyser, while samples for total phosphorus (P) and total potassium (K) analysis were prepared in a MARs Xpress microwave digester in a reverse Aqua Regia matrix, followed by analysis on an Agilent ICP-OES spectrometer. Available phosphorus (P) was determined following Olsen extraction followed by colorimetric analysis. Exchangeable bases (Ca, Mg, K and Na) were determined using atomic absorption spectrometry using ammonium acetate as the extracting agent. Soil pH was determined in water using the pH electrode method with a ratio of 1:2.

5.2.3 Grain yield

In all experiments, maize was harvested at physiological maturity within a net plot of 2.25 m by 3 m including three centre rows in each plot, leaving at least two rows on each side of the centre rows to minimize edge effects. After harvesting, total plant and cob numbers were recorded, and total cob weight determined in the field using a digital scale accurate to two decimal places in grams. Grain moisture content was determined using a moisture tester (Dickey John Mini GAC, Minneapolis USA). Grain yield in each plot was then converted to yield per hectare on a 12% moisture basis.

5.2.4 Total nutrient uptake

Total nutrient uptake was assessed in the final season of each phase of the experiments. For Phase 1, total nutrient uptake was assessed at the end of the long rainy season in 2016, while for Phase 2, total nutrient uptake was assessed at the end of the long rainy season in 2018. Nutrient uptake in grain and stover was calculated following determination of grain and stover nutrient concentrations at the Lancrop Laboratories in the United Kingdom. For this, representative subsamples of air-dried stover and grain were oven dried for 48 hours at 60 °C and then ground to pass a 1 mm screen. Total grain and stover nitrogen (N) contents were determined by Dumas combustion on a LECO Trumac CNS analyser. Other macro and micronutrients were determined by inductively coupled plasma emission spectrometer following ashing at 500 °C and digestion in a reverse Aqua Regia matrix. Nutrient uptake in grain and stover were determined as a function of grain and stover nutrient concentrations, and grain and stover dry matter yields respectively. Total nutrient uptake for each nutrient was then calculated as the sum of grain and stover nutrient uptake in each treatment plot.

5.2.5 The RC-P Model

5.2.5.1 Model description

The RC-P model is a simple model designed to calculate the long-term recovery of fertilizer P (Wolf *et al.*, 1987). In the model, two dynamic pools of P are distinguished, a labile and stable pool. The labile pool is defined as that P stored in the soil that has an availability to crops equal to that of the labile fraction of broadcast fertilizer, while the stable pool comprises that store of soil P to which the time constants of transfer apply (Wolf *et al.*, 1987). Crops P uptake in the model is supplied from the labile pool, while the stable pool serves as a slow-release buffer that replenishes the labile pool. With time intervals of 1 year, the model calculates the P transfers between the pools, the uptake of P by the crop, and the resulting pool sizes (Wolf *et al.*, 1987).

5.2.5.2 Modelling P uptake in nutrient-depleted fields

The ability of the RC-P model to predict total P uptake following fertilizer P application in P depleted soils was assessed by comparing model predicted total P uptake, and estimated and measured total P uptake in Phase 2-NOT. The RC-P model was modified to account for direct uptake of P from placed fertilizer following fertilizer P placement in P depleted soils. Resulting predictions of total P uptake based on both the original and modified RC-P model were then compared with estimated total P uptake in the three cropping seasons, and against measured total P uptake in the last season of Phase 2-NOT. Full details on: (i) model input data and model parameters; (ii) determination of initial P pool sizes; (iii) accounting for direct uptake of placed fertilizer P in P depleted soils; (iv) modelling of P uptake in P depleted soils; and, (v) estimation of total P uptake following fertilizer P application in P depleted soils, are provided in Annex B.

5.2.6 Statistical analysis

Maize yield response to combined NPK application in Phase 2-NPK was evaluated as the difference in mean seasonal maize grain yield in NPK plots differing in past nutrient application. For this, a mixed effects linear model with grain yield as the response variable, and 'past treatment' and 'season' as fixed effects was fitted in R software (R Core Team, 2017) using the package 'lme4' (Bates *et al.*, 2015). A random effect of 'farm' was included in the model to account for differences between farms. Significant effects of model parameters on grain yield were evaluated using the 'lmerTest' package in R software (Kuznetsova *et al.*, 2017), while model estimated means and least significant differences (LSD) values for mean separation were computed using the 'predictmeans' package in R software (Dongwen *et al.*, 2018). To assess spatial-temporal patterns of crop productivity following combined NPK application in nutrient depleted soils, seasonal relative yield in former nutrient omission plots was calculated as the ratio of the grain yield in NPK plots with nutrients previously omitted, and the grain yield in the long-term NPK treatment in the same field. Plot level relative yields were then sorted in increasing order and plotted against the cumulative frequency. To assess short-term recovery of past N, P and K applications on soils with imbalanced nutrient stocks (Phase 2-NOT), we assessed differences in mean grain yields in superimposed nutrient omission plots with similar past nutrient application in the initial nutrient omission experiment (Phase 1). For this, grain yield data from Phase 2-NOT was subset based on each of the past treatments in Phase 1. Using each of these subset datasets, mixed models with grain yield as the response variable, and ‘new treatment’ and ‘season’ as fixed effects were fitted. A random term ‘farm’ was included to account for differences between farms. The resilience of soil nutrient stocks was assessed by evaluating temporal patterns in soil organic carbon and soil N, P and K concentrations. For these, differences in mean soil contents between and within treatments for soils sampled at different intervals in the same fields were evaluated using mixed models.

5.3 Results

5.3.1 Phase 1

5.3.1.1 Effect of sustained imbalanced nutrient applications on soil fertility and maize yields

Plot level means of selected soil properties, mean maize grain yield, and total N, P and K uptake in the last season of Phase 1 showed a strong influence of past continuous cropping with imbalanced or no nutrient applications on soil fertility and crop productivity in fields selected for Phase 2-NPK and Phase 2-NOT (Table 5.1). Mean available soil nutrients, maize grain yields, and nutrient uptake were generally larger in fields selected for Phase 2-NPK, which were dominated by fields with past manure applications prior to Phase 1 (Table 5.1). Both sets of fields were however characterised by low (<15 g kg^{-1}) mean organic carbon contents, with minimal differences in mean contents between treatments (Table 5.1). Sustained cropping with no fertilizer applications resulted in depletion of plant available nutrients as indicated by the small mean available P and exchangeable K concentrations in the control treatment plots for both Phase 2-NPK and Phase 2-NOT fields (Table 5.1). On the other hand, imbalanced PK applications resulted in larger soil concentrations of available P and exchangeable K compared with concentrations observed under balanced NPK application (Table 5.1). Larger mean exchangeable K concentrations following sustained imbalanced NK applications accompanied by small concentrations of available P indicated imbalanced availability of soil nutrients (Table 5.1). A similar pattern was observed for imbalanced applications of NP where soil available P concentrations were larger (>7 mg kg^{-1}) relative to those in treatments with no P applied (<4 mg kg^{-1}), while mean exchangeable K concentrations were small (Table 5.1).

Sustained cropping with no nutrient applications strongly affected yields as indicated by mean maize grain yields of 1.8 and 0.8 t ha^{-1} for fields selected for Phase 2-NPK and Phase 2-NOT respectively (Table 5.1). For both categories, balanced NPK application resulted in larger yields by up to 3 t ha^{-1} (Table 5.1). Imbalanced nutrient applications also resulted in depressed yields, especially where P and K availability was low e.g. the NK and NP treatments for fields selected for Phase 2-NOT (Table 5.1).

For both Phase 2-NPK and Phase 2-NOT fields, mean total N, P and K uptake were largest and smallest in the NPK and control treatment plots respectively (Table 5.1). Near similar mean total N uptake in the PK treatment for the two field categories was indicative of similar degree of N limitation (Table 5.1). The very low (1.5 kg P ha^{-1}) mean total P uptake observed for the NK treatment in Phase 2-NOT fields indicated very strong P limitations in these fields, while limitations were less strong in Phase 2-NPK fields (Table 5.1). Mean total K uptake of 10.5 kg K ha^{-1} in the NP treatment in fields selected for Phase 2-NOT, compared with mean uptake of 51.4 kg K ha^{-1} uptake for the same treatment in fields selected for Phase 2-NPK also indicated very strong K limitations in fields selected for Phase 2-NOT.

Table 5.1: Mean values of selected soil properties (0 – 20cm), maize grain yield, and total nutrient uptake after the long rainy season of 2016 (end of Phase 1) in: fields (*n* = 13) selected for establishment of balanced NPK application trials (Phase 2-NPK); and in fields (*n* = 4) selected for establishment of superimposed nutrient omission trials (Phase 2-NOT), in Sidindi, western Kenya.

Selection category	Parameter	Past Treatment				
		Control	PK	NK	NP	NPK
Phase 2-NPK	OC (g kg^{-1})	12.2	12.2	12.6	12.5	12.3
	Olsen P (mg kg^{-1})	3.8	8.4	3.6	7.3	6.9
	Exch. K (cmol kg^{-1})	0.25	0.38	0.41	0.21	0.26
	Grain yield (t ha^{-1})	1.8	2.6	3.4	4.2	5.1
	N uptake (kg ha^{-1})	19.9	26.4	58.3	79.9	85.5
	P uptake (kg ha^{-1})	2.6	5.0	5.5	8.9	10.2
	K uptake (kg ha^{-1})	14.4	30.7	65.9	51.4	71.1
Phase 2-NOT	OC (g kg^{-1})	13.8	14.0	13.0	13.5	13.3
	Olsen P (mg kg^{-1})	2.3	8.8	2.8	7.5	7.5
	Exch. K (cmol kg^{-1})	0.15	0.40	0.34	0.11	0.20
	Grain yield (t ha^{-1})	0.8	2.3	0.6	2.0	3.8
	N uptake (kg ha^{-1})	11.8	23.0	24.1	42.9	68.1
	P uptake (kg ha^{-1})	1.2	3.5	1.5	4.1	6.1
	K uptake (kg ha^{-1})	5.2	18.0	13.2	10.5	36.7

5.3.2 Phase 2-NPK

5.3.2.1 Maize yield response to NPK application in nutrient depleted soils

Mean maize grain yields following balanced NPK application in plots differing in past nutrient applications indicated strong yield response to NPK application on strongly depleted soils (Table 5.2). In three out of four seasons, mean maize yields in treatment plots with nutrients previously omitted were not significantly different from yield in the long-term NPK treatment plot (Table 5.2). Significantly ($P<0.05$) smaller yields relative to yield in the long-term NPK treatment plot were, however, observed in the second cropping season in the former control, PK, and NK treatment plots. Significantly

(*P<0.05*) smaller yields observed in the former control treatment plots compared with yield in plots under past PK, NK and NP applications in the second cropping season (Table 5.2) indicated that yield response to combined NPK application was mostly limited by low P and K stocks.

Table 5.2: Mean maize grain yield response (t ha^{-1}) to NPK application in experimental Phase 2-NPK, in fields (n = 13) previously under seven consecutive seasons of nutrient omission trials (Phase 1), in Sidindi, western Kenya.

Season†	Past treatment‡					
	Control	PK	NK	NP	NPK	LSD
SR 2016	2.1 [a]	2.5 [a]	2.7 [a]	2.9 [a]	3.0 [a]	
LR 2017	5.5 [a]	6.7 [bc]	6.5 [bc]	7.0 [cd]	7.8 [d]	
SR 2017	4.3 [a]	4.5 [a]	4.2 [a]	4.4 [a]	4.5 [a]	0.9
LR 2018	5.4 [a]	5.4 [a]	5.9 [a]	5.6 [a]	5.4 [a]	

Grain yield values in the same row followed by a different superscript are significantly different at P<0.05)
LSD refers to least significant difference between means and applies for all rows
†LR and SR refer to long and short rainy seasons respectively
‡Refers to treatments in Phase 1

5.3.2.2 Spatial temporal patterns of maize yield response to NPK application in nutrient depleted soils

Cumulative frequency plots of relative yield across multiple fields demonstrated the spatial temporal variations in yield response to NPK application between fields in plots with similar past imbalanced nutrient applications (Fig. 5.2). Temporal variations were strongest in former control treatment plots as indicated by the large differences in cumulative frequency distributions between seasons (Fig. 5.2a). These plots also accounted for the largest proportion of cases with relative yield less than 1, especially in the first two cropping seasons (Fig. 5.2). The productivity of these plots improved in subsequent seasons as indicated by the shift to the right of cumulative frequency lines, and the larger incidence of relative yield values greater than 1 (Fig. 5.2a). Where plots had past PK, NK and NP applications, there were small temporal variations in yield response to NPK application, as indicated by the small differences in the cumulative frequency distributions between seasons (Figs. 5.2b, 5.2c & 5.2d). These treatment plots were also characterised by a smaller and steadily declining proportion of fields with relative yields less than 1, compared with plots with no nutrients previously applied.

The spread of seasonal relative yield values demonstrated the spatial variation in yield response to NPK application in these nutrient depleted soils (Fig. 5.2). Where no nutrients were previously applied, spatial variation was strongest in the first two cropping seasons (Fig. 5.2a). In these two seasons, maize yield in 30% of plots was less than half of that attained in the long-term NPK treatment plot in the same field (Fig. 5.2a). On the other hand, about 10% of plots gave yields equal to or larger than that in the long-term NPK treatment plot (Fig. 5.2a), illustrating the strong differences in yield response to NPK between fields. Observed spatial variations declined with continued application of balanced NPK as indicated by the narrowing of the spread of relative yield values in subsequent seasons (Fig. 5.2a). Strong spatial variations were also observed in plots that had received PK and NP applications in the past (Fig. 5.2b & 5.2d), while variation was less strong for plots previously receiving NK applications (Fig. 5.2c). In contrast with observations made for the former control treatment plots, observed spatial variations persisted over time in plots with past PK and NP applications as indicated by the similar spread of relative yield values across the four cropping seasons (Fig. 5.2b & 5.2d).

Where fields had no past manure applications prior to Phase 1, relative yields less than 1 in the first two cropping seasons in plots previously under control, PK and NK treatments indicated reduced yield response to NPK applications (Figs. 5.2a, 5.2b & 5.2c). For the same fields, similarity of relative yield values in treatment plots under past NK and NP applications in the first two cropping seasons (Fig. 5.2c & 5.2d) indicated that spatial patterns were less strong in soils strongly depleted in P and K. Large relative yield values in the second cropping season in plots with past NP applications (Fig. 5.2d), and in the third and fourth seasons in the former control, PK, and NK treatment plots (Figs. 5.2a, 5.2b & 5.2c) illustrated improvements in crop yield response with multiple applications of NPK in these strongly depleted soils.

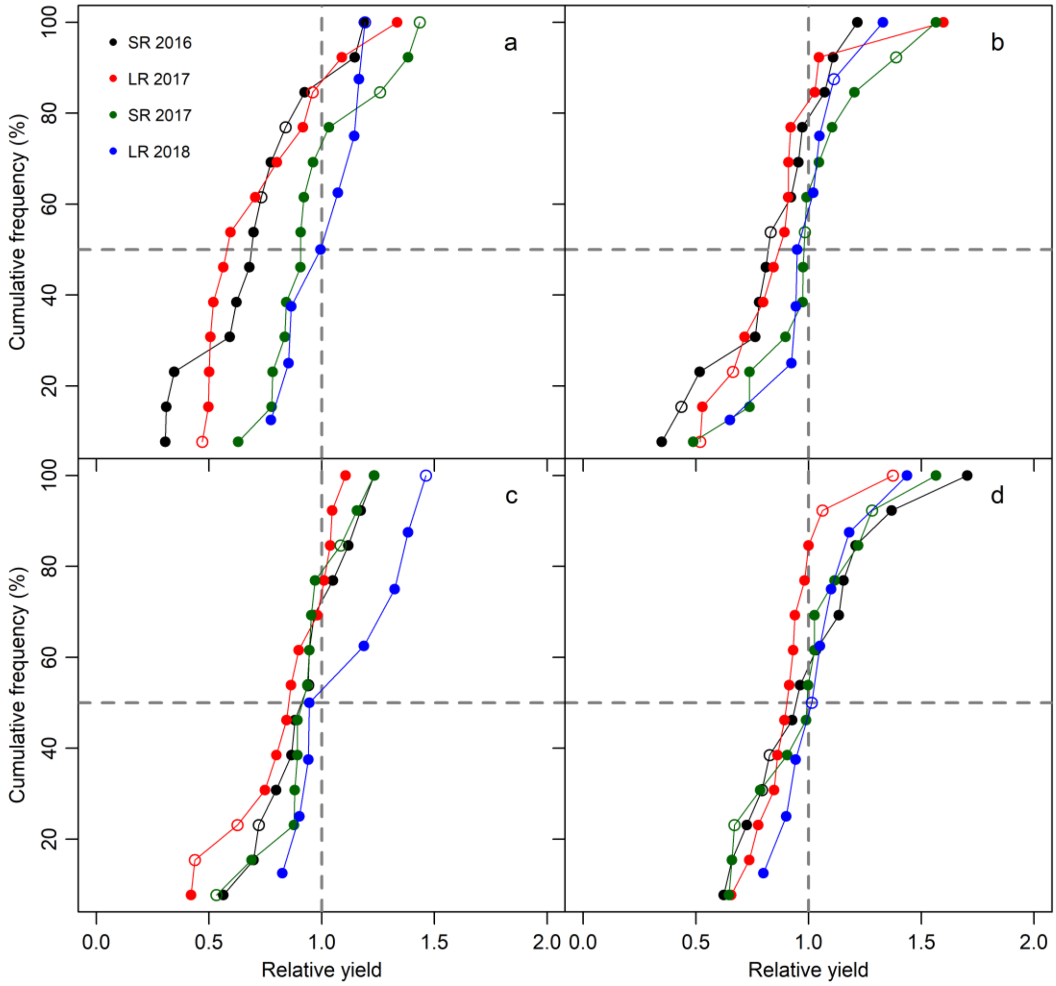

Fig. 5.2: Cumulative frequency (%) of relative maize grain yield over four cropping seasons following NPK application in: (a) former control treatment plots; (b) former PK treatment plots; (c) former NK treatment plots; and, (d) former NP treatment plots. SR and LR refer to short and long rainy seasons respectively. Open symbols indicate fields without past manure applications prior to Phase 1.

5.3.2.3 Influence of varied nutrient application regimes on resilience of soil nutrient stocks

Soil organic carbon contents did not significantly differ between and within treatments (Fig. 5.3a). Small and declining mean SOC contents in the control treatment in the second sampling period (2016) indicated stronger depletion of the organic carbon pool in soils where no nutrients had been applied (Fig. 5.3a). Depletion appeared to be less strong following supply of N, P and K in Phase 2-NPK as indicated by less strong decline in SOC contents in the third sampling period (Fig. 5.3a). Concentrations of soil available P were significantly ($P<0.05$) influenced by both treatments imposed, and the length of application period (Fig. 5.3b). In the first sampling period, mean available P concentrations were not significantly different between treatments (Fig. 5.3b). In this sampling period, mean available P concentrations were less than 8 mg kg^{-1} across all treatments, with smaller concentrations observed in the NK treatment where no P was supplied (Fig. 5.3b). Significant differences in available P concentrations between treatments were observed in the subsequent sampling period, with the PK treatment showing significantly ($P<0.05$) larger available P concentrations, compared with treatments where no P had been applied (Fig. 5.3b). Larger mean available P concentrations in the second sampling period in treatments receiving P indicated build-up of soil P stocks, while stocks in plots without P supplied remained stable (Fig. 5.3b). in this sampling period, mean soil available P concentrations in the PK treatment were significantly ($P<0.05$) larger than that in plots without P applied, and that in the PK treatment plot in the first sampling period (Fig. 5.3b). This indicates particularly stronger accumulation of applied P for this treatment. Conversion of nutrient omission plots to full NPK plots in phase two of the experiment resulted in larger soil available P concentrations in plots with no P previously applied (Fig. 5.3b). Significant ($P<0.05$) differences in soil available P concentrations between the former PK treatment plot and the former NK treatment plot however persisted, illustrating the gradual build-up of P stocks at application rates of 40 kg P ha^{-1}.

Mean soil exchangeable K concentrations differed significantly ($P<0.05$) between treatments and sampling periods (Fig. 5.3c). In the first sampling period, exchangeable K concentrations were largest in the NK treatment plot, with mean concentrations significantly ($P<0.05$) larger than those in the control and NP treatments where no K was applied (Fig. 5.3c). In the second sampling period, exchangeable K concentrations in the NK and PK treatment plots increased further, while those in other treatment plots declined (Fig. 5.3c). Resulting mean exchangeable K concentrations for the NK and PK treatments were significantly ($P<0.05$) larger than those in the control, NP, NPK treatment plots (Fig. 5.3c). Balanced NPK application in Phase 2-NPK of the experiment resulted in a sharp increase in exchangeable K concentrations in treatments with K previously omitted (Fig. 5.3c). Significant ($P<0.05$) differences in exchangeable K concentrations between the former NK treatment plot and treatment plots with K previously omitted however persisted (Fig. 5.3c).

Soil total N contents did not significantly differ between treatments in both Phase 1 and Phase 2-NPK (Fig. 5.3d). However, in the first two sampling periods in Phase 1, total N contents were smallest in treatments with no N applied, and largest in the NK treatment (Fig. 5.3d). N application in Phase 2-NPK of the experiment in treatment plots with no N previously applied resulted in significantly ($P<0.05$) larger total N contents in these plots in the third sampling period, compared to contents in the first sampling period (Fig. 5.3d). Similar to observations made for total N, mean total P contents did not vary significantly among treatments irrespective of sampling period (Fig. 5.3e). Soil total P contents however increased over time with continued fertilizer P application (Fig. 5.3e). Soil total K contents were not significantly different between and within treatments (Fig. 5.3f). The temporal patterns observed in the first two sampling periods did not reflect the treatments that had been imposed, with larger mean soil total K contents observed in the NP treatment where no K had been applied (Fig. 5.3f). Subsequent K application in this treatment did not result in improvements in total soil K contents, while improvements were observed in the former control treatment plot (Fig. 5.3f).

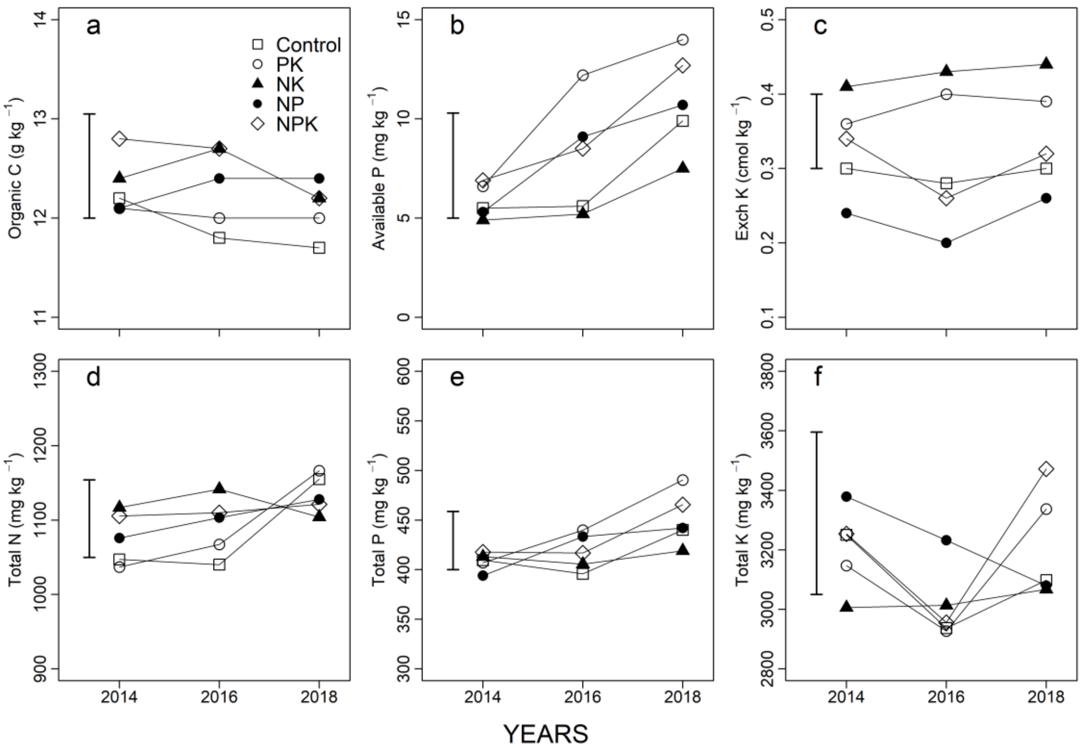

Fig. 5.3: Temporal changes in mean: a) soil organic C; b) soil available P; c) soil exchangeable K; d) total soil N; e) total soil P; and, f) total soil K), in on-farm nutrient response experiments (*n* = 13), after three (2014) and seven (2016) consecutive seasons of nutrient omission trials (Phase 1), and after three consecutive (2018) seasons of balanced NPK application (Phase 2-NPK). Symbols reflect treatments in Phase 1 of the experiment.

5.3.2.4 Effects on soil pH, and availability and uptake of secondary nutrients

Soil pH declined in all treatments with N applied (Fig. 5.4). The decline in soil pH was only significant (*P<0.05*) in treatments with N applied, including NK, NP and NPK in Phase 1 (2014 and 2016) and all plots in Phase 2 (2018). Differences between treatments including N and the control were significant in 2014 and 2016, except for the NK treatment in 2014 (Fig. 5.4).

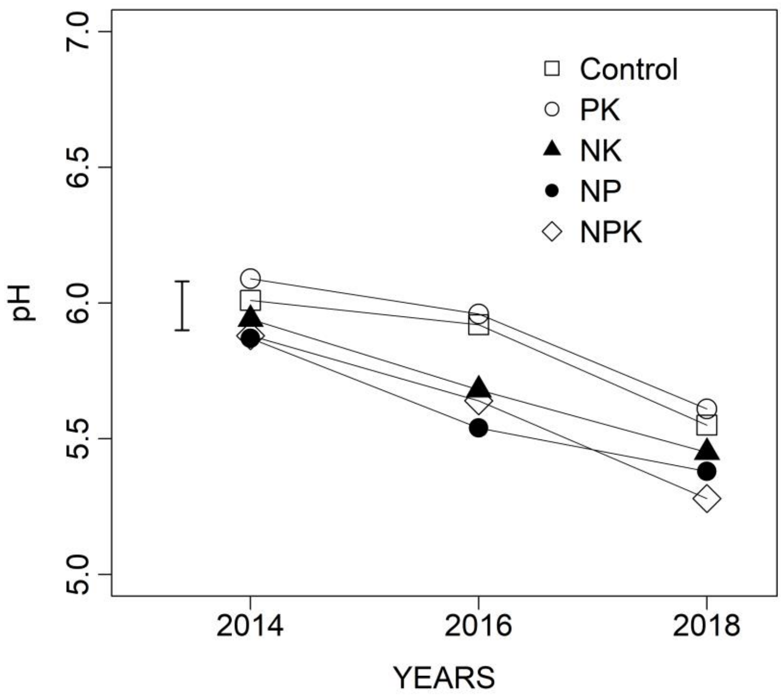

Fig. 5.4: Temporal changes in soil pH in on-farm nutrient response experiments (n = 13), after three (2014) and seven (2016) consecutive seasons of nutrient omission trials (Phase 1), and after three consecutive (2018) seasons of balanced NPK application (Phase 2-NPK). Symbols reflect treatments in Phase 1 of the experiment.

Grain uptake of magnesium (Mg) and calcium (Ca) was poorly related to soil Mg and Ca concentrations (Fig. 5.5). In Phase 1 of the experiment, significantly ($P<0.05$) larger grain Mg uptake was observed in treatments with N applied, while treatment plots without N applied showed significantly ($P<0.05$) larger mean soil Mg concentrations compared with the NP and NPK treatments (Fig. 5.5a). Grain Ca uptake in Phase 1 was also significantly larger in treatments with N applied compared to that in the no-input control treatment (Fig. 5.5b). Mean soil Ca concentrations were also smallest in the NP and NPK treatments (Fig. 5.5b). This suggests larger amounts of Mg and Ca had been removed due to the previous higher maize yields in treatments where N had been applied, and in particular the NP and NPK treatments (Njoroge *et al.*, 2017b). This is supported by the increased Mg uptake in previously N omitted treatment plots following N application in Phase 2-NPK, and the associated decline in soil Mg concentrations in these plots (Fig. 5.5a).

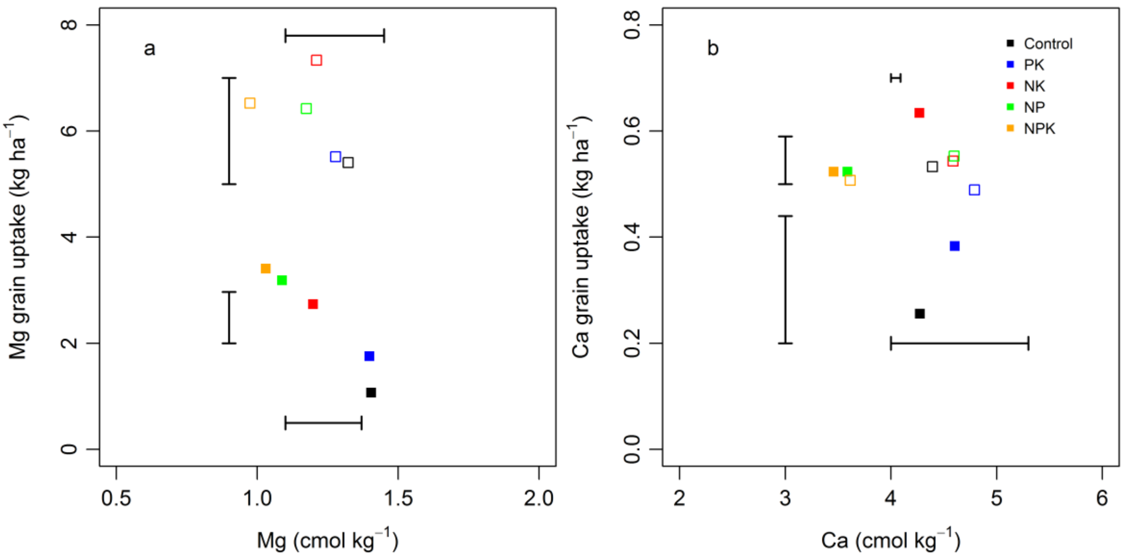

Fig. 5.5: Relationship between mean treatment: a) soil Mg contents (cmol kg^{-1}) and grain Mg uptake (kg ha^{-1}); and b) soil Ca contents (cmol kg^{-1}) and grain Ca uptake (kg ha^{-1}) in select fields (*n* = 5) fields after seven consecutive seasons of nutrient omission trials (Phase 1), and four consecutive seasons of balanced NPK application in the previously nutrient omission treatment plots (Phase 2-NPK) in Sidindi, western Kenya. Closed squares represent Phase 1, while open squares represent Phase 2-NPK. Error bars are LSD. Lower horizontal and vertical error bars represent mean separation for Phase 1, while upper horizontal and vertical error bars represent mean separation for Phase 2-NPK.

5.3.3 Phase 2-NOT

5.3.3.1 Recovery of N, P, and K in soils with past imbalanced nutrient applications

Differences in mean maize yield response between NPK and nutrient omitted sub-plots in Phase 2-NOT were used to quantify the magnitude of N, P and K limitations, and also assess the short-term recovery of fertilizer N, P and K applied in Phase 1 (Table 5.3). Long-term PK, NK and NP applications resulted in strong N, P and K limitations respectively as indicated by the significantly (*P<0.05*) smaller yields observed in all cropping seasons in the PK, NK and NP sub-plots, compared with yields in the NPK sub-plots where past treatments were similar (Table 5.3). Where the past treatment was a no-input control, significantly (*P<0.05*) smaller yields were observed in the PK, NK and NP sub-plots compared to the NPK sub-plot. This demonstrates strong N, P and K limitations following continuous cropping with no nutrients applied (Table 5.3). Limitations were strongest for P as indicated by the very small yields observed in this sub-plot in subsequent seasons (Table 5.3). The 2.7 t ha^{-1} difference in yield between the NPK and NP sub-plots in the first cropping season in plots is notable as it highlights the need for K fertilizers in strongly depleted soils. This is confirmed by the persistently smaller yields observed with NP application compared with NPK application in these former control treatment plots (Table 5.3). In the former PK treatment plots, similar yields in the NK, NP and NPK sub-plots, and significantly ($P<0.05$) smaller yields in the PK sub-plot in the first cropping season pointed to strong N limitations, while P and K stocks were sufficient (Table 5.3). P and K stocks however declined rapidly as indicated by the increasing difference in yield between the NK and NP sub-plots, and the NPK sub-plot in subsequent seasons (Table 5.3). In the former NK treatment plots, significantly ($P<0.05$) smaller yields in the NK sub-plot compared to other sub-plots in the first cropping season confirmed strong P limitations following repeated N and K applications (Table 5.3). N and K were however not limiting in this first cropping season as indicated by the similar yields between the PK and NPK sub-plots, and the significantly larger yields in the NP sub-plots (Table 5.3). While yields in the PK sub-plot declined steadily over time, yields in the NP sub-plot matched those in the NPK sub-plot in subsequent seasons indicating continued availability of plant available K stocks while N stocks rapidly declined (Table 5.3). In the former NP treatment plot, significantly ($P<0.05$) smaller yields observed in the NP sub-plot compared with other sub-plots in the first cropping season confirmed strong K limitations following sustained applications of only N and P (Table 5.3). In the same season, N and P were not limiting as indicated by similar mean yields between the PK and NK sub-plots, and the NPK sub-plot (Table 5.3). Yield differences greater than 1 t ha^{-1} between the NPK and NK subplot in the second cropping season, and the NPK and PK sub-plot in the third cropping season pointed to increasingly severe N and P limitations, indicating minimal accumulation of applied N and P following past applications of N and P only (Table 5.3). In the former NPK treatment plot, mean yields did not differ significantly between sub-plots in the first cropping season (Table 5.3), indicating adequate supply of N, P and K in the nutrient omitted sub-plots. However, in the second cropping season, yield in the NK sub-plot was significantly ($P<0.05$) smaller than that in the NPK sub-plot, while in the third cropping season, yield in the PK sub-plot was significantly ($P<0.05$) smaller than that in the NPK sub-plot (Table 5.3). These significantly smaller yields coupled with the increasing yield difference between the NPK and NP sub-plots indicate strongly increasing N, P and K limitations in these formerly balanced NPK plots. This illustrates minimal accumulation of N, P and K under moderate balanced NPK applications.

Recovery of past N applications was largest following past NK and NP applications as indicated by the similarity in yield between the PK and NPK sub-plots in all three cropping seasons in treatment plots where NK and NP had previously been applied (Table 5.3). Recovery however declined sharply as indicated by the greater than 1 t ha^{-1} difference in yields between the NPK and PK sub-plots in the third cropping season

(Table 5.3). Observed similar maize grain yields between the NK and NPK sub-plots in the first season in all treatments plots with P previously applied indicated rapid recovery of P applied in the past (Table 5.3). Larger yields in all three cropping seasons in the NK sub-plot in treatments under past PK applications compared with those which had received NP or NPK in the past (Table 5.3) indicated that recovery of past P application was largest following past P application in the absence of N. Similar to N and P, recovery of past K application appeared largest in treatment plots with past imbalanced K applications. This was particularly the case for past NK applications, as indicated by the significantly ($P<0.05$) larger yield in the NP sub-plot compared to the NPK sub-plot in treatment plots with past NK applications in the first cropping season (Table 5.3). The similar yields observed between these two sub-plots in subsequent seasons further indicated sustained recovery of past K applications in the NK treatment plots, suggesting large K reserves (Table 5.3). On the other hand, the steadily increasing differences in yield between the NPK and NP sub-plots in treatment plots under past balanced NPK applications pointed to small and rapidly declining K reserves (Table 5.3).

Table 5.3: Mean maize grain yield in t ha^{-1} for on-farm (n=4) superimposed nutrient omission trials (Phase 2-NOT) established in fields previously under eight consecutive seasons of nutrient omission trials (Phase 1) in Sidindi, western Kenya.

Season	Past Treatment[‡]	Treatment				
		PK	NK	NP	NPK	LSD
LR 2017	Control	2.6^{a}	1.3^{a}	2.9^{a}	5.6^{b}	2.2
	PK	2.5^{a}	6.3^{b}	5.4^{b}	6.0^{b}	1.8
	NK	4.2^{a}	0.5^{b}	6.2^{c}	4.0^{a}	1.6
	NP	6.4^{a}	5.7^{a}	1.8^{b}	6.2^{a}	1.7
	NPK	5.5^{a}	4.7^{a}	5.9^{a}	6.3^{a}	1.9
SR 2017	Control	1.5^{ab}	0.1^{a}	2.2^{ab}	3.1^{b}	2.2
	PK	1.3^{a}	3.5^{b}	3.7^{b}	4.4^{b}	1.8
	NK	2.8^{a}	0.1^{b}	2.9^{a}	3.1^{a}	1.6
	NP	3.3^{c}	1.5^{ba}	1.0^{a}	2.9^{bc}	1.7
	NPK	2.3^{ab}	1.8^{a}	2.4^{ab}	3.8^{b}	1.9
LR 2018	Control	1.4^{ab}	0.9^{a}	2.4^{abc}	4.6^{c}	2.2
	PK	2.4^{a}	3.9^{ab}	3.6^{ab}	5.2^{b}	1.8
	NK	2.1^{ab}	0.7^{a}	3.9^{c}	3.5^{bc}	1.6
	NP	1.9^{ab}	2.8^{ab}	1.3^{a}	3.2^{b}	1.7
	NPK	1.7^{a}	3.0^{b}	2.2^{ab}	3.9^{b}	1.9

LSD refers to least significant difference between means and applies across rows
[‡]*Refers to treatments in Phase 1*

5.3.3.2 Fate of applied K in soils with depleted and imbalanced nutrient supplies

Mean sub-plots soil exchangeable K stocks in the plough layer at the start of the final season of Phase 2-NOT and mean total K uptake at the end of the final season of Phase 2-NOT provided an insight on the fate of applied fertilizer K in soils with depleted and imbalanced nutrient supplies (Table 5.4). In treatment plots without past K applications (Control and NP), soil exchangeable K stocks were smaller in the NP sub-plots compared with sub-plots that received K (Table 5.4). This illustrates build-up of soil K stocks in these K depleted soils following fertilizer K applications, while contents remained low where no K was applied. In the former control treatment plots, the observed larger total K uptake in the NP sub-plots compared to the PK sub-plots illustrates strong mining of K where no K is supplied, while applied K in the PK sub-plot accumulated (Table 5.4). Similarly, where treatment plots had past applications of K, smaller soil K contents in the NP sub-plots compared to sub-plots with K applied indicated mining of previously accumulated stocks (Table 5.4). Under balanced NPK applications, the smaller mean soil K contents and total K uptake observed where past applications were NP illustrate that larger applications of fertilizer K may be required to enhance soil K stocks and crop productivity under conditions of severe K mining. Where K mining was less severe, more rapid build-up of K was observed as indicated by the larger soil K contents and total K uptake following NPK application in the former control treatment plots (Table 5.4).

Table 5.4: Mean sub-plots soil exchangeable K stocks (kg ha^{-1}) at the start of the third season, and total K uptake (kg ha^{-1}) at the end of the third season for on-farm (n=4) superimposed nutrient omission trials (Phase 2-NOT) in Sidindi, western Kenya.

Parameter	Past Treatment[ǂ]	Treatment			
		PK	NK	NP	NPK
Soil K in plough layer (kg ha^{-1})	Control	301	237	190	342
	PK	465	562	301	465
	NK	375	489	260	307
	NP	208	184	138	234
	NPK	263	287	231	263
Total K uptake (kg ha^{-1})	Control	15	37	36	50
	PK	19	55	50	57
	NK	28	28	30	40
	NP	16	28	13	21
	NPK	18	33	14	43

[ǂ]*Refers to treatments in Phase 1*

5.3.3.3 Modelling of fertilizer P uptake in P depleted soils

Initial RC-P model predicted total P uptake in treatment plots with and without fertilizer P applied showed general good agreement with measured total P uptake in the final season of Phase 1 (Fig. 5.6). A recovery fraction of 0.04 of the initial P labile pool appeared to effectively capture observed patterns of P uptake following seven seasons of fertilizer P application in the NPK treatment plot, and fertilizer P omission in the NK treatment plot. Observed differences in predicted and measured P uptake in plots receiving P indicated strong differences in the size of the labile P pool between farms (Fig. 5.6).

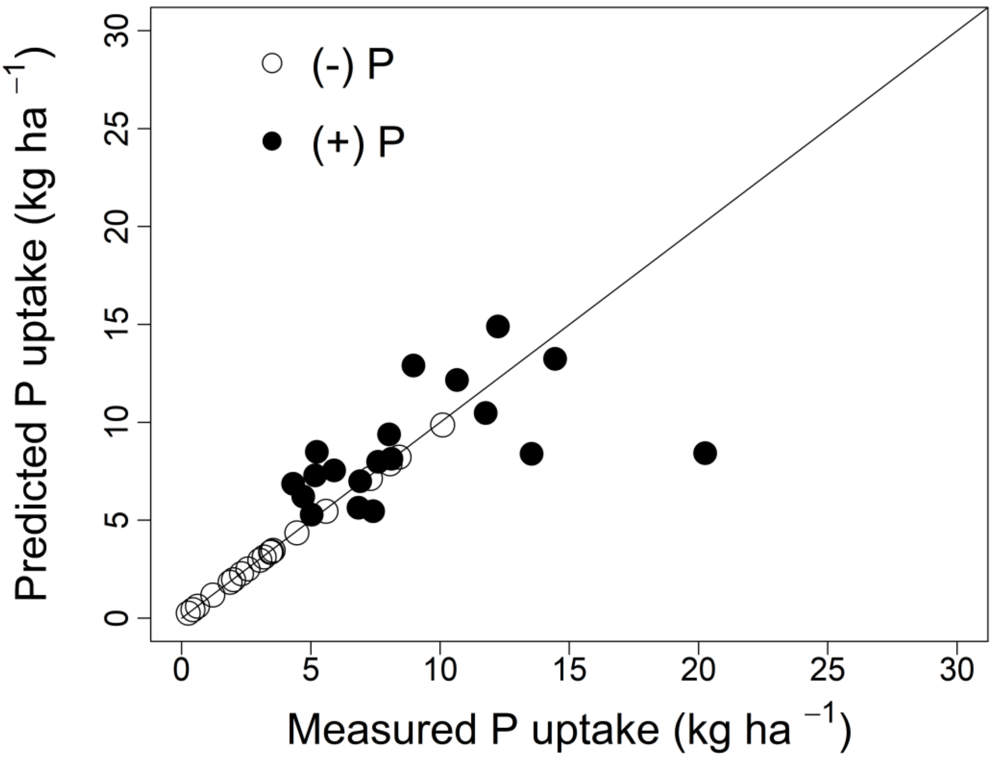

Fig. 5.6: Measured and RC-P model predicted P uptake in the treatment plots with and without P applied in the seventh consecutive season of on-farm nutrient omission trials (Phase 1) in Sidindi, western Kenya. The diagonal line is the 1:1 line. Measured total P uptake in the seventh season of Phase 1 was used to model labile and stable P pools in the seventh season. Using these estimates, the model was back cast to estimate initial labile and stable pools at the start of Phase 1. The model was then re-run using these estimated initial values to predict P uptake with and without fertilizer P in the seventh season of Phase 1.

Seasonal total P uptake following fertilizer P application in treatment plots with past applications of NK in Phase 2-NOT of the experiment illustrated P uptake patterns in strongly P depleted soils (Fig. 5.7). Estimated total P uptake based on the previously observed relationship between grain yield and measured total P uptake in Phase 1 of the experiment (Annex B, Fig. B1) showed good agreement with measured total P uptake in the third cropping season (Fig. 5.7). Estimated first season total P uptake greater than 10 kg ha^{-1} across all three fields following P application of 40 kg P ha^{-1} in these strongly P depleted soils indicated substantial uptake of the applied fertilizer P (Fig. 5.7). Uptake patterns in subsequent seasons also indicated substantial uptake of applied P with some seasonal fluctuations (Fig. 5.7). This was in contrast to predicted P uptake with the original RC-P model which suggested initial minimal uptake of applied P, with gradual improvements in uptake in subsequent seasons as the size of the labile pool increased (Fig. 5.7). The modified RC-P model which accounted for direct uptake of P from placed fertilizer at a recovery rate of 0.3 of the labile fraction of applied fertilizer was in much closer agreement with estimated and measured P uptake (Fig. 5.7). This was particularly the case in very strongly P depleted soils which had a very small labile P pool (Fig. 5.7a & 5.7b).

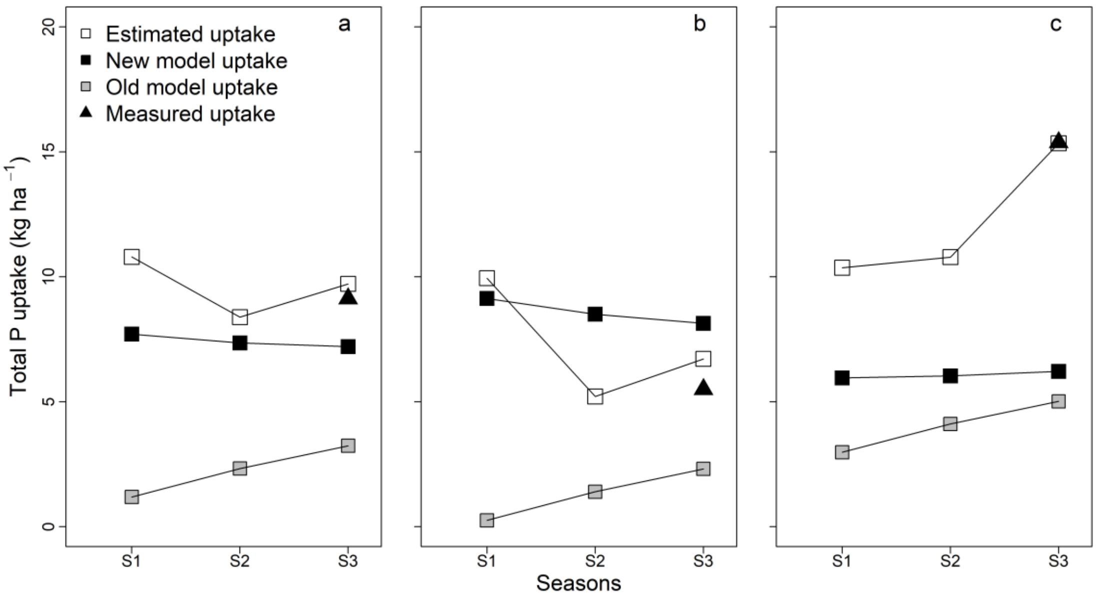

Fig. 5.7: Estimated, measured and RC-P modelled total P uptake across three consecutive seasons in three P depleted soils following balanced NPK fertilization in Phase 2-NOT.

5.4 Discussion

5.4.1 Strong yield response to balanced fertilization in nutrient depleted soils

Continuous cropping without or with imbalanced nutrient applications during Phase 1 of the experiment resulted in soils with depleted nutrients stocks. Nutrient depletion was strongest in fields without past manure applications before Phase 1 of the study, as illustrated by low concentrations of available nutrients in the soil and small mean maize grain yields (Table 5.1). Crops were responsive to NPK application on all fields. Even in the most strongly N, P and K depleted plots, mean maize grain yield was 5.5 t ha^{-1} in the second season of Phase 2-NPK, while mean yields in subsequent seasons were similar to those observed in the long-term NPK treatment plot (Table 5.2). Yields with NPK in the former control plots also matched those under long-term NPK in all three seasons of Phase 2-NOT (Table 5.3). We did not encounter non-responsive fields to NPK fertilization, in contrast to findings by earlier studies in western Kenya, and in the larger SSA region (Tittonell and Giller, 2013; Zingore *et al.*, 2008; Kihara *et al.*, 2016; Njoroge *et al.*, 2017a). The occurrence of such non-responsive soils has mainly been attributed to additional constraints of secondary and micronutrients following sustained cropping with no or insufficient nutrient inputs (Vanlauwe *et al.*, 2015; Kihara *et al.*, 2017; Njoroge *et al.*, 2017a). Observed yields under NPK fertilization at low soil Mg and Ca availability however indicated no additional nutrient constraints beyond those of N, P and K in the clay rich soils of the study area, strongly contrasting to findings of Zingore *et al.* (2008) for depleted sandy soils of Zimbabwe. These findings indicate that in tropical soils with high clay contents as present in western Kenya, crop productivity can be increased with balanced NPK fertilization alone. Such soils do not therefore require prior soil fertility restorations with e.g. large repeated applications of manure (Zingore *et al.*, 2008; Rusinamhodzi *et al.*, 2013). Opportunities are therefore present for the improvement of crop productivity over large areas of the eastern African highlands where soils and cropping systems mirror those of western Kenya, by focusing on balanced applications of NPK. This is in contrast to the costlier high input strategies based on large applications of nutrients to replenish soil fertility such as those previously recommended by Sanchez *et al.* (1997). Strongly P or K depleted soils however required multiple NPK fertilizer applications before yield levels were equivalent to yield in plots that received continuous NPK fertilizer, resulting in stronger temporal patterns in yield response (Fig. 5.2). This indicates the need to adjust initial yield expectations for NPK fertilization in the first one to two seasons by about 1 – 2 t ha^{-1} on strongly P and K depleted soils.

5.4.2 Imbalanced nutrient applications affect the resilience of soil nutrient stocks

Differences in nutrient application regimes resulted in strong differences in plant available P and K stocks over time, while changes were minimal for total nutrient stocks (Fig. 5.3). Smaller uptakes of N, P or K following imbalanced applications resulted in larger accumulation of available stocks, while accumulation was less strong under balanced fertilization where uptake was large (Fig. 5.3 & Table 5.4). While mean SOC contents were generally small across treatments, declining SOC contents in treatment plots with no N applied (Fig. 5.3) were illustrative of the negative effects of continued cropping without N inputs on the soil organic carbon pool even when the initial pool is small. Imbalanced applications including 60 kg K ha^{-1} resulted in significantly larger exchangeable K concentrations compared to plots with no K applied after only three cropping seasons (Fig. 5.3). In contrast, exchangeable K concentrations were not significantly different between plots receiving balanced NPK supply and those with no K applied even after six cropping seasons (Fig. 5.3). Given mean total K uptake of 71 kg K ha^{-1} in the NPK treatment plots at the end of Phase 1 (Table 5.1), it is clear that applied fertilizer K was just sufficient to meet crop uptake requirements, but insufficient to substantially build up soil K stocks. Similarly, observed mean soil available P concentrations of 8 mg kg^{-1} and 5 mg kg^{-1} in the NPK and NK treatment plots respectively, after six seasons of seasonal applications of 40 kg P ha^{-1} in Phase 1, indicated that fertilizer P application rates were not sufficient to saturate P adsorption capacity. Much larger broadcast (Van der Eijk *et al.*, 2006) applications of fertilizer P and K would therefore be necessary for the build-up of depleted soil P and K stocks, but it is unlikely that such an approach would be economically viable.

5.4.3 Accounting for recovery of accumulated nutrient stocks

Maize yield patterns in nutrient omitted sub-plots in Phase 2-NOT indicated strong short-term recovery of accumulated nutrient stocks. In treatment plots with PK and NK applications in Phase 1, maize yields in the NK and NP sub-plots did not differ from those in the NPK sub-plots over the three cropping seasons in Phase-2 (Table 5.3), indicating recovery of accumulated P and K stocks. Fields with sufficient stocks of P or K, e.g. due to manure use (Kihanda *et al.*, 2006; Rusinamhodzi *et al.*, 2013), allow therefore short-term adjustments in the recommended amounts of fertilizer P and K, reducing costs for farmers. Manure is a key source of nutrients in crop-livestock farming systems such as those of western Kenya (Castellanos-Navarrete *et al.*, 2015), yet the available quantities are frequently not adequate to match crop nutrient uptake requirements across all fields of the farm (Tittonell *et al.*, 2010b). Simplified decision support tools that account for residual effects of previous applications of organic and inorganic nutrient inputs on current plant N, P and K requirements can therefore help farmers and extension service providers fine tune recommended fertilizer applications at the field level. This would allow more efficient allocation of available organic and inorganic nutrients. The recent quantification of the fertilizer P and K equivalents of the contribution of past manure applications in this study area (Njoroge *et al.*, 2019) provides indicative values for short-term adjustment of fertilizer P and K requirements in such decision support tools.

5.4.4 Placement improves recovery of applied fertilizers in nutrient depleted soils

Placed P-fertilizer gave a strong recovery of around 30% in the first season, even on the strongly P depleted soils in Phase 2-NOT, much larger than can be expected for the applied TSP fertilizer with a soluble P fraction of 0.8 (Wolf *et al.*, 1987). The observed recovery is similar to that previously reported by Van der Eijk (1997) following application of 22 kg P ha^{-1} in P depleted soils of western Kenya. This large recovery at low P application rates has been related to enhanced uptake due to higher concentration of soil P directly below the plant roots following placement of P fertilizer (Van der Eijk *et al.*, 2006; Sanchez, 2019), and improved root proliferation in this P enriched soil layer (Ma *et al.*, 2013). This allows P uptake to proceed at a maximum rate even at low application rates (Van der Eijk *et al.*, 2006). In the original RC-P model, crops take up P from the labile pool, with the labile P fraction of applied fertilizer P contributing to the increase in size of this labile pool (Wolf *et al.*, 1987). A uniform value of P recovery for this labile pool is then assumed by most P uptake models, e.g. Wolf *et al.* (1987), Greenwood *et al.* (2001), and Heppell *et al.* (2016). Initial yield response to P application is therefore expected to be small as a consequence of the small size of the initial labile P pool in P depleted soils. Our results suggest a combined P-uptake from the labile pool and direct uptake from placed fertilizer, bypassing this labile pool, improving the predicted fertilizer P uptake from the RC-P model. This indicates that even in soils with strong P sorption (Sanchez, 2019) and P depleted soils, modest applications of spot-placed fertilizer P can help smallholder farmers boost crop productivity. For this approach to succeed, farmers need to be equipped with knowledge on where and how to apply available P fertilizers (Van der Eijk *et al.*, 2006). Farmer training should therefore be based on the ‘4R nutrient stewardship’ approach: the right source, application rate, in the right place and at the right time in the growing season (Johnston and Bruulsema, 2014). Introduction of simple and affordable tools to mechanise seeding and placement of basal applications should be considered, for enhancing yield and efficiency on smallholder fields (Aune *et al.*, 2017).

5.5 Conclusions

Maize yields responded strongly to NPK fertilization on all soils, even those with very depleted nutrient stocks. Within three cropping seasons of NPK fertilization, maize yield in treatment plots with depleted N, P and K stocks matched the yields of plots under long-term NPK application. Past imbalanced nutrient applications resulted in strong spatial variation in the yield response to NPK fertilization, due to differences in available soil P and K stocks. Imbalanced applications of PK and NK resulted in strong accumulation of P and K stocks, while P and K accumulation in the soil was very limited under balanced NPK applications. Soil concentrations of Mg and Ca also declined significantly at higher yields, though small soil concentrations did not affect yields with balanced NPK fertilization. Recovery of accumulated N, P and K was largest in the first season of uptake from the soil nutrient pool. Accounting for direct uptake of placed fertilizer P resulted in improved RC-P model predictions of total P uptake following fertilizer P application in P exhausted soils.

Our findings highlight the potential for immediate increase in crop productivity with balanced macronutrient application in typical tropical soils with a high clay content as found in western Kenya after long periods of depletion. Secondary nutrients and micronutrients need only to be supplied when deficiencies are observed in the field: soil tests proved not informative of crop response. Accounting for animal manure use in the past and recent applications of P and K fertilizer can help to further fine-tune balanced NPK recommendations. Further, placement strongly improved recovery of applied P and should be recommended and demonstrated as a standard practice. Our results strongly support the approach of feeding the crop and allowing soil fertility to recover gradually, rather than feeding the soil.

5.6 Acknowledgement

This study was facilitated through funding from Agrium to the International Plant Nutrition Institute (IPNI), for research on 4R Nutrient Stewardship in western Kenya. Joses Muthamia and Joseph Sewe are acknowledged for assistance with field management.

Chapter 6

General Discussion

6.1 Overview

Low crop productivity is a key contributor to persistent food insecurity in sub-Saharan Africa (SSA). Projected future increases in food demand are expected to place populations in SSA at an even greater food security risk if current crop productivity levels persist (Van Ittersum *et al.*, 2016). Crop productivity intensification on existing farmlands is urgently required if the SSA region is to become more food secure (Koning *et al.*, 2008; Tilman *et al.*, 2011), with reduced reliance on substantial imports (Van Ittersum *et al.*, 2016), and expansion of agriculture into marginal lands and forest areas (Brink and Eva, 2009; Nkamleu, 2011). Increased fertilizer use is central (Africa Fertilizer Summit, 2006) to addressing nutrient deficiencies that limit crop productivity (Mueller *et al.*, 2012). Fertilizer use in the predominant smallholder farming systems of SSA is however characterized by large variations in crop yield response at the regional and farm level (Vanlauwe *et al.*, 2006; Tittonell *et al.*, 2008b; Kihara *et al.*, 2016). Improvements in crop productivity have therefore failed to match investments in fertilizer use, and crop yields of important crops are still low. Improved understanding of crop yield response patterns to fertilizer applications is therefore required if substantial increases in crop productivity are to be attained.

Using western Kenya as a case study and maize as the test crop, this thesis aimed at providing means for the improved prediction of the expected crop yield response to fertilizer application under heterogeneous smallholder farming conditions of SSA. A summary of the main findings and implications is presented in Fig. 6.1. In Chapter 2 we demonstrated that differences in yield response to fertilizer N, P and K applications vary strongly over space and time, presenting challenges for the development of effective site-specific recommendations. We further demonstrated that current methods for soil analysis do not adequately explain the expected yield response to fertilizer applications, and recommended the additional inclusion of field characteristics and past management history. This led us to investigate the field level factors causing variability in maize yield response to fertilizer N, P and K applications in Chapter 3. In this chapter, we showed that accounting for past manure applications decreased the uncertainty in yield response to fertilizer applications, illustrating the need to account for past field management when making field level decisions on fertilizer use. We subsequently quantified the contribution of past manure application in fertilizer N, P and K equivalents, providing a criterion for fine-tuning fertilizer NPK recommendations at the field level based on past applications of manure. In Chapter 4, we showed that the QUEFTS model did not adequately predict maize yield responses to balanced and imbalanced fertilizer applications under variable soil fertility conditions. This was linked to poor estimation of soil N, P and K supply with current relationships based on soil chemical data. In Chapter 5, we demonstrated immediate maize yield response to balanced NPK applications on strongly nutrient depleted soils typical of the tropics and concluded that such soils do not require prior investments to rebuild soil nutrient stocks for crop yields to be increased. Findings in this chapter also showed that recovery of fertilizer P was higher than expected for these strongly P-adsorbing soils, also in the first year of application. This was linked to spot placement of fertilizer which results in high concentration of soil P directly below plant roots even at low application rates. Based on these findings, we recommended the demonstration of proper fertilizer placement as a standard practice for smallholder farmers in SSA. Findings from this thesis have improved our understanding of the patterns of maize yield responses to fertilizer applications in heterogeneous smallholder farming systems of western Kenya. Most importantly, these findings have provided insights on a framework for disaggregating, and managing observed variability in yield response to fertilizer applications that can be upscaled in comparable farming systems of SSA.

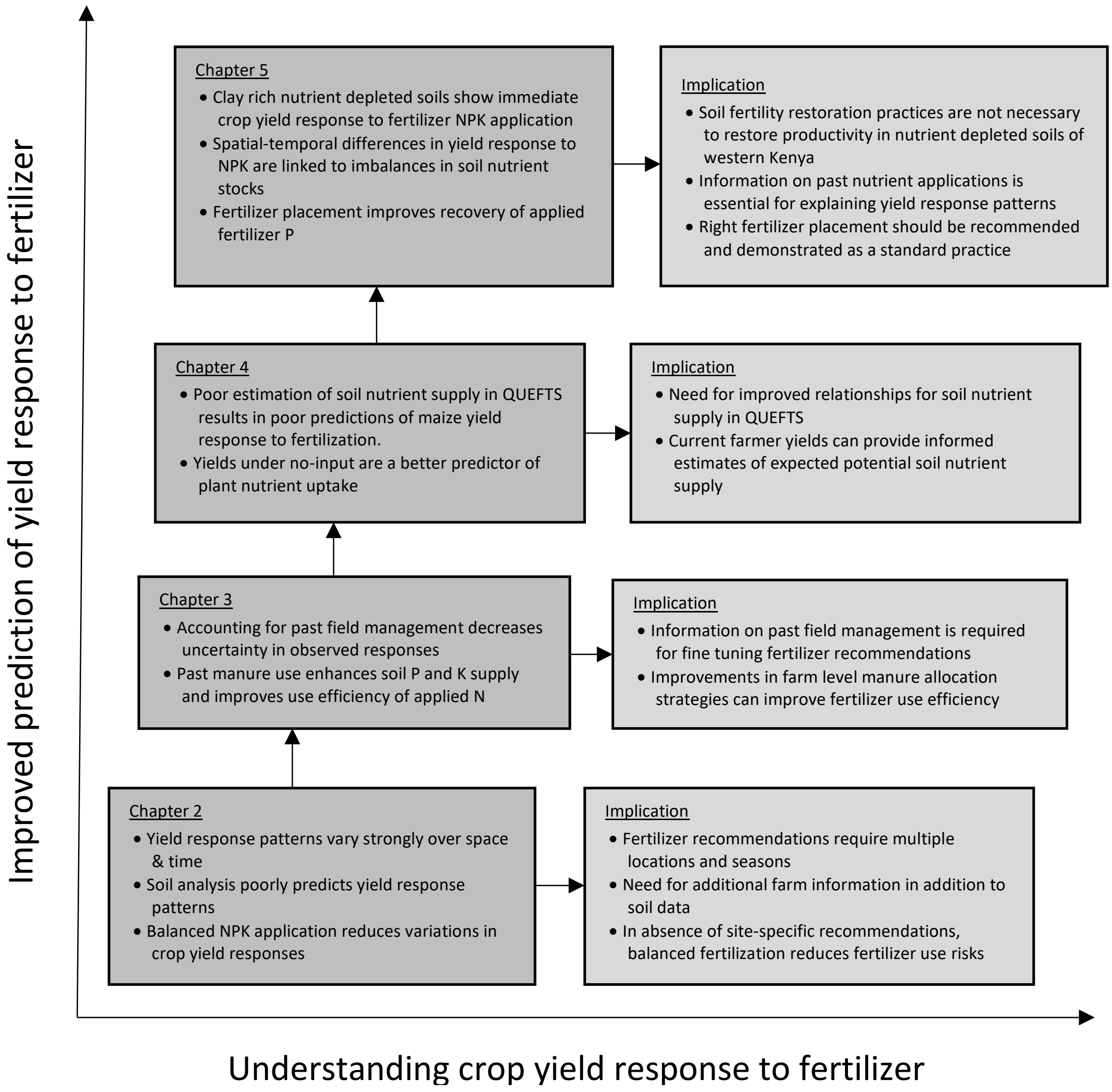

Fig. 6.1: Summary study findings and implications

6.2 Crop productivity restoration on nutrient depleted soils

High nutrient depletion rates in smallholder farming systems (Stoorvogel and Smaling, 1990) have contributed to the large proportion of nutrient depleted soils in the SSA region (Tan *et al.*, 2005). Subsequently, soil fertility depletion has been identified as the fundamental biophysical cause of declining per capita food production in the region (Sanchez and Palm, 1996), and increased soil fertility is a precondition for initiating growth in crop productivity (Crawford *et al.*, 2005). The replenishment of soil fertility has been previously proposed for crop productivity restoration in nutrient depleted soils of SSA (Sanchez *et al.*, 1997). In this approach, a one-time but large application of fertilizer P or rock phosphate (Buresh *et al.*, 1997), and strategies involving the use of legumes and mineral fertilizers (Giller *et al.*, 1997) were proposed to build up soil P and N stocks respectively. However, while one-time large fertilizer P applications substantially improve soil P stocks, they are characterized by low fertilizer use efficiency (Van der Eijk *et al.*, 2006), and short-term beneficial effects on crop productivity as available stocks are not entirely available for crop uptake (Nziguheba *et al.*, 2002). This strongly questions the rationale for investing in soil fertility replenishment if improvements in soil fertility do not result in sustained improvements in crop productivity. High capital costs of fertilizer, and machinery required for one-time applications (Van der Eijk *et al.*, 2006) further mean that such approaches are out of the reach of the often resource constrained smallholders. While a cost shared approach was envisaged to address farmer limitations in resources (Sanchez *et al.*, 1997), such an approach has failed to take off.

To restore crop productivity in nutrient depleted soils, I propose a focus on regular fertilizer applications aimed at supplying the crop with nutrient uptake requirements for a single season. Findings from my study (Chapter 5) clearly demonstrated that seasonal applications of 150, 40, and 60 kg ha^{-1}, of fertilizer N, P and K respectively were sufficient to immediately increase crop productivity in strongly nutrient depleted soils (Fig. 5.2), while at the same time gradually building soil nutrient stocks (Fig. 5.3). While the use of organic resources such as manure has been identified as key to restoring the productivity of nutrient depleted soils (Zingore *et al.*, 2008), simulation studies in western Kenya region have demonstrated the superiority of mineral fertilizer over manure in rapidly restoring crop productivity to levels attained prior to nutrient depletion (Tittonell *et al.*, 2008a). Results from my study allow evaluation of these model predictions using actual yield measurements. By focusing on fields that had no manure application prior to the study, effects of nutrient depletion and fertilization on crop productivity are clear to see (Fig. 6.2). In Phase 1 of the study, good maize yields are only attained with balanced NPK application, while strongly declining yields in plots with nutrients omitted illustrate the strong effects of nutrient depletion on crop productivity (Fig. 6.2). Despite the very small yields in the eighth season of nutrient omission, maize yields immediately increased to levels comparable to those under sustained NPK applications, even in the strongly nutrient depleted control treatment plots (Fig. 6.2a). This confirms simulation model results of Tittonell *et al.* (2008a), illustrating that strategies that help farmers access enough fertilizers to meet seasonal crop uptake requirements are sufficient to restore crop productivity on strongly nutrient depleted soils.

Compared to large one-time fertilizer applications, the smaller fertilizer applications rates in my proposed approach, and the yield benefit associated with the starter effect of freshly applied fertilizers (Van der Eijk, 1997), would translate in higher fertilizer use efficiency. Immediate yield benefits observed with a fertilizer based approach compared to delayed benefits when manure is used (Zingore *et al.*, 2008; Tittonell *et al.*, 2008a) also fit within farmers expectations of immediate crop productivity benefits for technologies to be adopted (Ojiem *et al.*, 2006). The lower input costs, and the ease of adaptability in small scale farming systems of SSA where most of the work is done by hand (Van der Eijk *et al.*, 2006), further illustrate that the proposed approach is more in tune with the socio-economic reality of smallholder farming in SSA, compared to large one-time applications. For this approach to succeed, farmers require training on right placement of fertilizers to ensure optimal uptake of nutrients. Spot placement of fertilizer directly below seeds results in a nutrient enriched zone directly below plant roots, allowing for enhanced nutrient uptake (Van der Eijk *et al.*, 2006). When not correctly implemented, spot placement can result in scorching of seeds when fertilizers come into direct contact with germinating seeds, negatively affecting yields. The 4R nutrient stewardship framework (Johnston and Bruulsema, 2014) provides an easily adaptable platform for farmer training on best fertilizer use practices. Such a platform which lays the foundations for efficient use of fertilizers is integral for the success of the proposed low input strategy.

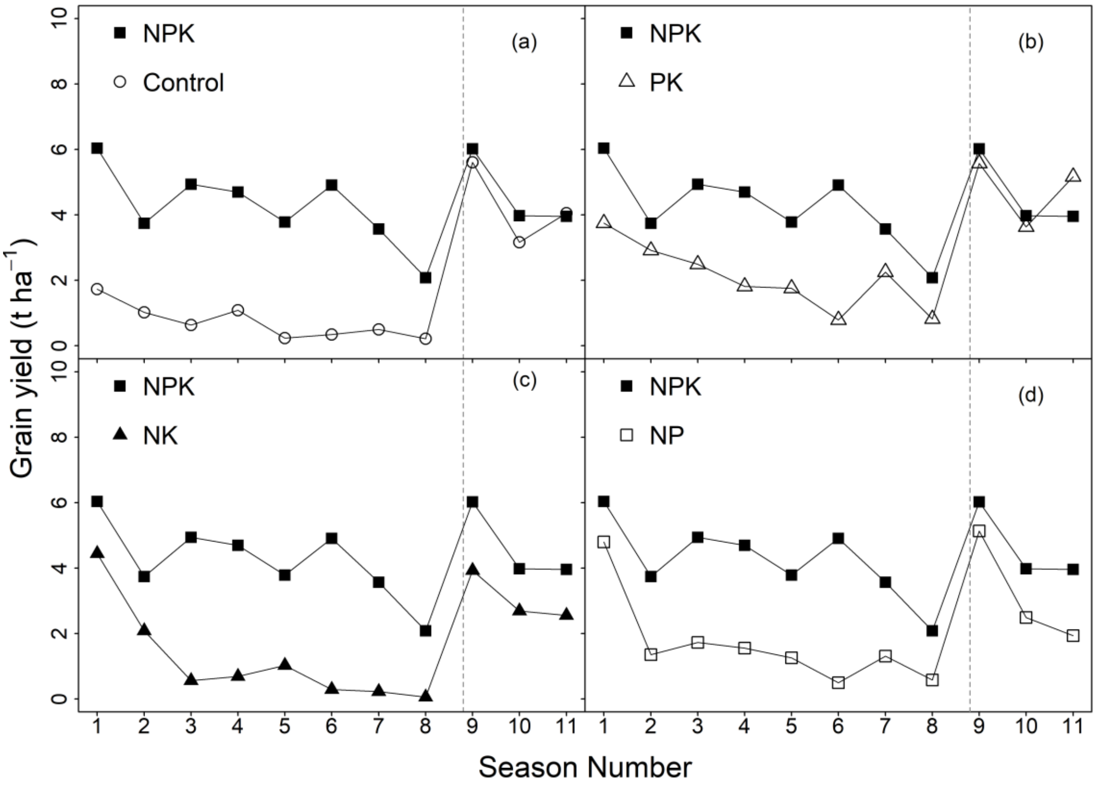

Fig. 6.2: Mean maize yield patterns with balanced and imbalanced fertilization in fields without past manure application. Black squares represent long-term NPK treatment plots. Dotted vertical lines indicate onset of full NPK application (Phase 2-NOT) in plots with nutrients previously omitted.

6.3 Optimizing fertilizer use efficiency in smallholder farming systems of SSA

6.3.1 Potential for optimized fertilizer use efficiency

Findings from this study have clearly demonstrated the potential of fertilizer use to substantially increase crop productivity within smallholder farming systems of SSA. Simultaneous improvement of crop productivity and nutrient use efficiency (NUE) (Fixen *et al.*, 2015) of applied nutrients is however required for sustainable crop productivity intensification. Agronomic efficiency (AE) defined as the increase in yield per unit of nutrient applied (Dobermann, 2007), provides a means for short-term evaluation of nutrient use efficiency. Results from this study provide an opportunity for evaluating opportunities for optimizing fertilizer use efficiency in smallholder farming systems.

Using data from Phase 1 of this study, AE in the first two cropping seasons was calculated as the difference in maize grain yield (kg ha^{-1}) in NPK treatment plots and in treatment plots with a particular nutrient omitted, divided by the quantity of the particular nutrient applied (kg ha^{-1}) in the NPK treatment plot. For example, agronomic efficiency of nitrogen (AEN) was calculated as:

$$AEN = (Y_{npk} - Y_{pk})/N_{appl} \quad (12)$$

Where Y_{npk} and Y_{pk} refer to maize grain yields (kg ha^{-1}) in the NPK and PK treatment plots respectively, and N_{appl} refers to quantity (kg ha^{-1}) of fertilizer N applied. Mean AEN was 15 and 14.4, mean agronomic efficiency of phosphorus (AEP) 10.3 and 31.7, while mean agronomic efficiency of (AEK) was 7.4 and 14.4 in the first and second cropping seasons respectively (Table 6.1). Observed mean AEN was similar to values of 14.4 and 14.3 kg kg^{-1} reported for the OFRA and TAMASA projects (ten Berge *et al.*, 2019), two recently concluded large scale nutrient response trials in major maize growing regions of SSA. Mean AEP was however smaller than values of 23.9 and 29 kg kg^{-1} for the TAMASA project, and for a meta-analysis of on-farm trials in western Kenya respectively (Kihara and Njoroge, 2013), while mean AEK was larger than a value of 3.2 and less than 1 kg kg^{-1} for the TAMASA study, for an on-farm study in Zimbabwe respectively (Kurwakumire *et al.*, 2014). While these mean values indicate positive benefits of nutrient use on maize grain yields, wide ranges in the agronomic efficiency of applied N, P and K between fields were observed (Table 6.1) that illustrate strong differences in nutrient use efficiency between fields. This highlights the need for strategies aimed at optimizing nutrient use efficiency at the field level for sustainable crop productivity intensification. In the following subsection, assessment of patterns of AE between fields is conducted to assess options for optimizing AE within smallholder farms.

Table 6.1: Mean and range of agronomic efficiency of, N, P and K (kg grain/kg nutrient applied) in Phase 1 (*n=23*).

Season	AEN	AEP	AEK
LR 2013	15.0 (-0.4 – 31.6)	10.3 (-54.5 – 83.8)	7.4 (-44.5 – 50.1)
SR 2013	14.4 (-11.4 – 31)	31.7 (-66.2 – 102.8)	7.4 (-25.4 – 75.7)

6.3.2 ISFM based approaches for optimizing fertilizer use efficiency

The adoption of integrated soil fertility management (ISFM) has been proposed as a key pathway for optimizing agronomic efficiency (AE) of applied nutrients and improving crop productivity in smallholder farming systems of SSA (Vanlauwe *et al.*, 2010). Key aspects for optimizing AE based on the ISFM approach include: (i) the use of improved crop germplasm; (ii) the correct use of fertilizer; (iii) appropriate organic resource management; and (iv) adaptation to local conditions (Vanlauwe *et al.*, 2010).

In Chapter 4, it was shown that maize grain yield in unfertilized control treatment plots is a good indicator of soil fertility, while in Chapter 3, past manure application was linked to enhanced soil nutrient supply. Boundary lines of maximum agronomic efficiency (AE) for the relationships between AEN, AEP and AEK, and yield in control plots in fields with and without past manure applications can therefore provide further insights into variations in AE between fields (Fig. 6.3). Maximum AEN was largest (25 kg kg^{-1}) at control yields larger than 0.7 t ha^{-1}, while at smaller control yields, maximum AEN was 16 kg kg^{-1} (Fig. 6.3a). Low AEN at small control yields was prevalent in fields without past manure applications especially in the second cropping season, while high AEN was common in fields with past manure applications (Fig. 6.3a). Observed patterns are in line with those of Vanlauwe *et al.* (2011) who reported mean AEN of 17 and 31 kg kg^{-1} for outfields characterised by limited applications of manure and homefields characterised by large manure applications, respectively. These findings subsequently support the co-application of fertilizer N and organic resources in poor quality fields as proposed in the ISFM conceptual framework (Vanlauwe *et al.*, 2010). In farming systems of western Kenya, farmers typically remove crop residues for use as animal fodder and manure serves as the only source of organic matter. The co-application of manure with fertilizer N has been found to significantly enhance AEN (Vanlauwe *et al.*, 2011) due to additional quantities of N provided by manure (Palm *et al.*, 2001). Manure application also increases SOM (Zingore *et al.*, 2008), which improves AEN through enhanced crop N demand in poor soils (Vanlauwe *et al.*, 2010). Improvements in soil P supply following manure application also enhances the recovery of applied fertilizer N as discussed in Chapter 3. As manure is a scarce resource in smallholder farming systems of western Kenya (Tittonell *et al.*, 2010b), the co-application of fertilizer N and available quantities of manure in planting holes provides an opportunity for efficient use of scarce organic and inorganic nutrient resources at the farm level. Observed large variations in AEN at large control yields illustrate opportunities for further optimization of AEN in high fertility fields. Adaptations to local conditions by assessing yield response patterns as presented in the ISFM conceptual framework for optimizing AE (Vanlauwe *et al.*, 2010) is recommended.

In contrast to N, maximum AEP was highest (70 kg kg^{-1}) at low control treatment yields, and declined strongly at control yields larger than 2.5 t ha^{-1} (Fig. 6.3b). Similar patterns observed for multiple studies across SSA were related to increasing plant-available soil P with increasing soil fertility (Kihara and Njoroge, 2013). Low AEP at large control treatment yields in fields with past manure applications corroborates the strong effects of soil-available P on AEP, as past manure application was related to larger plant-available P (Chapter 3). Observed patterns indicate potential options for optimizing fertilizer P use efficiency on smallholder farmers' fields in western Kenya. In the short-term, fields without past manure applications require optimal fertilizer P application rates to optimize fertilizer use efficiency. While a maximum P application rate of 38 kg P ha^{-1} has been suggested for the western Kenya region (Kihara and Njoroge, 2013), low soil P stocks in soils without past manure applications may necessitate slightly larger P applications to enhance plant-available P. This should however include the application of fertilizer N to enhance the uptake of applied P (Kihara *et al.*, 2010). Targeted applications of manure on such fields is also recommended. On the other hand, fields with substantial amounts of manure previously applied can benefit from short-term adjustments in fertilizer P application rates by applying rates required for replacement purposes only (Kihara and Njoroge, 2013). In systems with substantial amounts of manure available, a longer-term ISFM based approach should include the rotational applications of manure within fields in a farm, with the subsequent adjustment of P application rates between fields based on manure application history.

Maximum AEK tended to decline with increasing control yields (Fig. 6.3c). Observed maximum AEK of about 40 kg of grain per kg of K applied at control yields less than 1 t ha^{-1} indicates that fertilizer K application should be a prerequisite in low fertility soils of western Kenya. Similar to AEP, high AEK at low control yields in fields without past manure applications suggests a scope for optimization of fertilizer K use efficiency based on past manure applications. While AEK generally declined with increasing control yields, large variations in AEK at control yields larger than 4 t ha^{-1} (Fig. 6.3c) suggests an additional scope for local adaptation to optimize AEK as previously discussed for AEN.

The discussion above illustrates a clear scope for optimization of fertilizer use efficiency within smallholder farming systems of SSA through ISFM based approaches. Integration of ISFM to optimize fertilizer use efficiency should however be applied within existing farming systems (Vanlauwe *et al.*, 2010). Suitable ISFM based approaches are therefore expected to differ from one farming system to another. Strategies that involve farmers and local experts to characterize current farming systems to identify opportunities and starting points for ISFM based approaches are required at the local level for targeted optimization of fertilizer use efficiency.

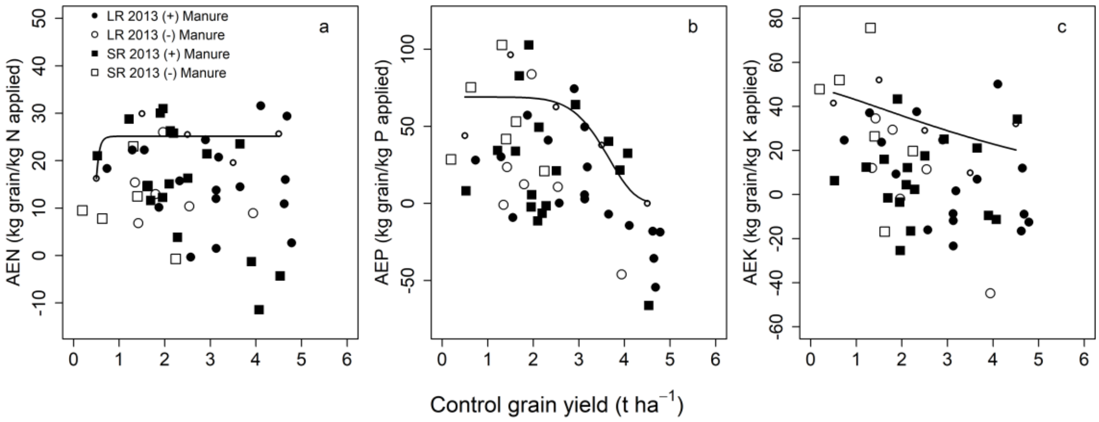

Fig. 6.3: Relationship between: a) agronomic use efficiency of nitrogen (AEN); b) agronomic use efficiency of phosphorus (AEP); and, c) agronomic use efficiency of potassium (AEK), and maize yield in control treatment plots at different levels of control yield in fields with and without past manure application. Boundary lines were fit using the three highest values of AEN, AEP or AEK respectively for every 1 t ha^{-1} increment in control yields.

6.4 Revisiting the non-responsive soils discourse

6.4.1 Quantification of non-responsive soils

The presence of strongly degraded soils on which crops respond poorly to fertilizer applications (Zingore *et al.*, 2007a; Kihara *et al.*, 2016) is often stated as one of the key factors hindering crop productivity intensification in smallholder farms of SSA. Subsequently, the term 'poor non-responsive soils' has been coined to describe degraded soils where application of NPK fertilizers does not result in increased crop productivity (Vanlauwe *et al.*, 2010). There however appears to be a lack of consensus on the specific criteria for identifying such poor non-responsive and low responsive soils. Some studies in western Kenya have used observed maize yields with NPK fertilization as a measure of responsiveness (Kihara *et al.*, 2016), while others have used monetary returns to NPK fertilizer use as a measure of responsiveness (Njoroge *et al.*, 2017a). Such distinct methodological differences are bound to invariably generate substantially different categorization of soils, with further expected differences in technological and policy recommendations. For example, in the study by Njoroge *et al.* (2017a), 57% of 44 sites which showed a value cost ratio (VCR) of less than 2 following application of 100, 30 and 60 kg ha^{-1} of N, P and K respectively were classified as poorly non-responsive in the long rainy season of 2014. With mean maize grain yield response to NPK of 4.7 t ha^{-1} (Njoroge *et al.*, 2017a), such classification raises a myriad of questions as one would expect that soils in this study are generally responsive. While VCR is a good indicator of the profitability of fertilizer use in smallholder farming systems (CIMMYT, 1988), it is in my view a poor discriminator of responsive and poorly responsive soils given that changes in grain and or fertilizer prices influence VCR. Similar maize yields under the same soil fertility conditions, with the same fertilizer inputs in different seasons will result in different VCRs if farmers are confronted with substantially different maize and or fertilizer prices. A soil previously delineated as ‘poor non-responsive’ soil in one season may then be classified as ‘responsive’ in a subsequent season or vice versa while soil conditions and yield response to fertilizer remain the same! Seasonal differences in maize yield response to NPK fertilization under the bi-modal rainfall system of western Kenya are also bound to influence the proportion of poorly responsive soils. Indeed, a reduction in mean yield response to NPK by 57% in the subsequent short rainy season in the same study resulted in only 3 out of 44 fields attaining a VCR larger than 2, with 93% of fields classified as poorly responsive (Njoroge *et al.*, 2017a). Such strong seasonal effects on maize yield response to NPK fertilization are in line with our findings in Chapter 5 where mean maize yield under long-term NPK fertilization was 3 t ha^{-1} in the short rainy season of 2016, and 7.8 t ha^{-1} in the subsequent long rainy season (Table 5.2). Reported occurrences of poorly responsive soils based on VCR are in my view then largely an issue of profitability of fertilizer use rather than responsiveness of soils, with distinct implications for farmers and policy makers. I therefore propose that the assessment of responsive and non-responsive soils should be strictly based on observed crop yield responses to fertilizer applications, with the profitability of such applications evaluated separately. Additionally, the strong effect of seasonality on maize yield response to NPK fertilization demands the use of multiple seasons experiments as a basis for evaluation of the occurrences of responsive and non-responsive soils in cropping systems such as those of western Kenya.

6.4.2 Explaining non-responsiveness

The occurrences of poor non-responsive soils has mainly been attributed to additional secondary and micronutrient deficiencies that are not addressed by fertilizer NPK applications (Njoroge *et al.*, 2017a; Kihara *et al.*, 2016; Zingore *et al.*, 2008), with the additional application of manure frequently proposed to alleviate these deficiencies. While this may be the case for strongly degraded sandy soils (Zingore *et al.*, 2008), findings in this thesis paint a different picture for higher clay content soils such as those of western Kenya. Results in Chapter 5 showed that low soil Mg and Ca concentrations did not influence maize yield response, and uptake of Mg and Ca with NPK fertilization (Fig. 5.5). Additionally, multiple NPK applications were required to substantially increase yields in strongly P and K depleted soils (Fig. 5.3). I therefore contend that from a plant nutrient availability perspective, poor maize yield responses to NPK applications in western Kenya are primarily influenced by limitations in soil N, P and K supply. For example, taking into account N, P and K application rates of 100, 30 and 60 kg ha^{-1} respectively in the previous studies by Kihara *et al.* (2016) and Njoroge *et al.* (2017a), and with expected recovery rates of about 0.5, 0.2 and 0.5 for N, P and K respectively, crop nutrient uptake from fertilizer would be approximately 50, 6 and 30 kg ha^{-1} of N, P and K respectively. Findings in Chapter 5 showed that at 5 t ha^{-1} yield, the uptake of 85, 10 and 71 kg ha^{-1} of N, P and K respectively was required, with smaller uptakes in fields without past manure applications resulting in mean yields of 3.8 t ha^{-1} (Table 5.1). Application rates of 100, 30 and 60 kg ha^{-1} of N, P and K respectively are therefore insufficient to supply plants with adequate plant available nutrients, given expected strong nutrient limitations on smallholder farms. Resulting maize yield response patterns are then likely reflective of differences in soil N, P and K supply between fields, and not truly a reflection of additional limitations in secondary and micronutrients. Indeed, findings from this study clearly showed that the significant contribution of past manure applications to larger maize yield response to NPK fertilization (Table 3.3) was related to improved soil supply of plant available P and K, and enhanced recovery of fertilizer N. This indicates that improvements in maize yield responses to NPK fertilization following manure applications are related to the strong influence of improved N, P and K availability which likely overrides effects of secondary and micronutrients. Results by Vanlauwe *et al.* (2006) which showed that fertilizer applications of 100 kg ha^{-1} each of N, P and K in strongly heterogenous fields across three different sites in western Kenya resulted in no differences in observed maize yield response to NPK between and within sites support my hypothesis. I therefore propose that studies aimed at identifying and explaining the occurrence of poorly responsive soils should first aim at supplying sufficient quantities of in particular P and K, before conclusions are drawn on the poor responsiveness, or otherwise of soils, and recommendations made.

6.5 Enhancing maize productivity in sub-Saharan Africa

6.5.1 The need for increased fertilizer applications

Improved food self-sufficiency in SSA requires substantial yield improvements in maize, the most important cereal food crop in the region (Shiferaw *et al.*, 2011). Findings from this study have shown that maize grain yields greater than 4.5 t ha^{-1} are possible once fertilization is right. Such yields are comparable to required mean country level yields of 4.5 t ha^{-1} for maize self-sufficiency in the East Africa region (ten Berge *et al.*, 2019). This illustrates the significance of fertilizer use in closing current yield gaps in maize (GYGA, 2019) in the SSA region as previously postulated by Mueller *et al.* (2012). It has recently been calculated that such yields would require minimum N, P and K application rates of 91, 10.7, and 57.1 kg ha^{-1} of N, P and K respectively (ten Berge *et al.*, 2019). Current nutrient application rates in the East Africa region are however 5.2, 3.9, and 0.3 kg ha^{-1} of N, P and K respectively (Sheahan and Barrett, 2017), highlighting a big mismatch between required and actual fertilizer application rates. While improvements in the targeting of fertilizer applications are an important first step in enhancing maize yield responses to fertilizer applications, such targeting will be of minimal use if farmers cannot access required quantities of fertilizers. Improved farmer access to fertilizers is required for farmers to apply the quantities required to sustain high yields.

Fertilizer use in smallholder farming systems of SSA is often limited by the high costs of fertilizer (Chianu and Mairura, 2012). To counter this and spur increased fertilizer use, various governments in the SSA region have committed significant portions of their annual budgets to reviving large-scale input subsidy programs (ISPs) (Jayne *et al.*, 2018). While these ISPs have been primarily aimed at increased fertilizer use to improve yields of staple cereals such as maize, yields remain low (FAO, 2018a). This raises a myriad of questions on the effectiveness of these programs, and suggests a change in approach. In the following sections, I briefly evaluate the effectiveness of current ISPs, and subsequently propose an alternative approach.

6.5.2 Evaluating the effectiveness of maize input subsidy programs

Second generation ISPs have been credited with recent increases in fertilizer use within smallholder farming systems of SSA (Sheahan and Barrett, 2017), and are currently the centerpiece of many African governments' agricultural development programs (Jayne *et al.*, 2018). While these ISPs have resulted in substantial increases in fertilizer use (Sheahan and Barrett, 2017), positive effects on maize productivity have been minimal (Mason and Tembo, 2015; Ricker-Gilbert and Jayne, 2017). A scrutiny of current ISPs illustrates underlying inadequacies in their structure and implementation. A major weakness of majority of ISPs is inefficiencies in the supply chain (Baltzer and Hansen, 2011), leading to frequent delays in supply of fertilizers to farmers (Baltzer and Hansen, 2011; Xu *et al.*, 2009). This results in delays in fertilizer applications, reducing the effectiveness of fertilizers applied. ISPs also frequently cover only a limited set of inputs, curtailing farmers ability to meet farm specific nutrient requirements. For example, the national accelerated agricultural inputs access program (NAAIAP) in Kenya mostly supplies Diammonium Phosphate (DAP) and Calcium Ammonium Nitrate (CAN), while our findings (Chapter 3) have clearly demonstrated the need for K fertilization to sustainably increase yields in the western Kenya region. Further, while a key goal of these second-generation ISPs was to ensure improved targeting of beneficiaries to enhance fertilizer use, this is rarely achieved. A review of Tanzania's 2009 ISP program indicated that the program did not allocate fertilizer to targeted beneficiaries any more efficiently than a random allocation would have (Pan and Christiaensen, 2012). In Malawi, despite using a community-based approach to target poor households, fertilizer subsidies failed to reach 46% of poor households while allocating inputs to 54% of non-poor households (Houssou and Zeller, 2011). Inability of ISPs to reach target beneficiaries has been largely linked to politically motivated targeting of beneficiaries as evidenced in Malawi, Ghana, and Kenya (Mather and Jayne, 2018; Mason *et al.*, 2016; Banful, 2011), and bias in allocation based on social standing within the community (Pan and Christiaensen, 2012; Mason and Smale, 2013). Based on the aforementioned challenges in the structure and implementation of current ISPs, I am of the view that in their current structure, ISPs will not spur the required increase in maize productivity, derailing efforts made towards improved targeting of fertilizer applications. An alternative approach is required.

6.5.3 Towards non-subsidy-based improvements in access to fertilizers

I propose a move away from ISPs towards a government led stakeholder inclusive approach aimed at structural and policy changes targeted at reductions in fertilizer cost (Fig. 6.4). As a first step, governments in SSA need to make sustained investments in development and improvement of inland transport. Poor inland transport significantly increases fertilizer costs, with inland transport accounting for 15-34% of fertilizer farm gate prices (Chianu and Mairura, 2012). Simulation studies in western Kenya previously showed that structural changes in fertilizer procurement which reduced fertilizer farm gate prices by 15% led to increases of 20-32% in farm incomes (Chianu *et al.*, 2011). Recent increased government investments in rail, road, and port infrastructures in the East Africa region are in line with this proposed framework, and are expected to significantly reduce port delays and inland transportation costs, with an expected reduction in fertilizer prices accessed by farmers. Subsidies on transport of fertilizers that ensure the availability of fertilizers at the same price throughout the country are also useful in promoting farmers' access to fertilizers. Policy changes that reduce barriers to entry into fertilizer markets and fertilizer distribution are also necessary to increase competition, improve efficiency and lower costs. For example, in Tanzania up to five agencies are mandated with controlling fertilizer imports, resulting in multiple fees that are eventually passed on to farmers (Jayne *et al.*, 2018). In Kenya, policy reforms that eliminated retail price controls, import licensing quotas, and foreign exchange controls are largely credited with the rapid growth in private fertilizer distribution networks in the past decade (Minde *et al.*, 2008). This has significantly reduced the distance between farmers and agrodealers in majority of rural areas, greatly expanding access to fertilizer, reducing fertilizer transport and transaction costs (Minde *et al.*, 2008). Enhanced stakeholder consultation is another key component of the proposed framework. Limited consultations and interactions between the various players in the fertilizer industry limit opportunities for synergy in efforts aimed at improvements in fertilizer use. Initiatives such as the recently reconstituted Kenya Fertilizer Roundtable (KeFERT) (https://ifdc.org/kefert/) are key in providing platforms for stakeholder consultations.

Structural and policy changes that improve the profitability of fertilizer use in maize are also an important part of the proposed long-term strategy. Poor yield response to fertilizer application negatively affects profitability of fertilizer use, reducing farmers incentive and ability to purchase fertilizers in subsequent seasons. Investments in research aimed at more responsive maize varieties, and improved prediction of expected yield response to fertilizer application are required to improve profitability of fertilizer use. Findings in this thesis have illustrated limitations in estimation of soil nutrient supply as a key factor limiting accurate maize yield response predictions. Such findings present opportunities for detailed research to identify more reliable methods for estimating soil nutrient supply, and predicting crop yield responses to fertilizer applications. Increased research funding to local universities and national agricultural research stations, and enhanced structural and human capacity by governments is required for significant advancements in such research areas to be made.

Targeted collaboration between research and extension is also required for passage of technologies developed from researchers to farmers. Extension systems in the majority of SSA countries are however inadequately equipped to meet the needs of farming communities (Swift and Shepherd, 2007). While extension agents recruited by fertilizer companies are helping to bridge this gap, the extension to farmer ratio remains low, resulting in large disparities in yield responses under researcher and farmer managed conditions (Jayne *et al.*, 2018). Investments aimed at improving the extension to farmer ratio, and equipping of extension agents with skills and resources for technology transfer are required. The high penetration of mobile devices and significant reductions in mobile services costs in the recent past has opened opportunities for mobile phone-based extension services. With lower operational costs and higher farmer reach, mobile phone-based extension services present opportunities for the cost-effective remodelling of extension systems in SSA.

Besides the cost of fertilizers and crop yield response to fertilizer application, profitability of fertilizer use is strongly influenced by maize grain output prices. Output prices accessed by majority of smallholder farmers in SSA are however usually low due to limited access to markets, the need to sell at harvest when supply is high and prices low due to cash constraints, and limited storage options. Low output prices affect the profitability of fertilizer use, limiting the ability of farmers to invest in fertilizers in the forthcoming season, resulting in a vicious cycle. For example, a countrywide survey in Malawi showed that while biological response of maize to fertilizer use was consistently high, less than 10% of sites indicated profitability at application of 45 kg nutrients ha^{-1} when maize was sold at harvest, compared to 55% of sites when maize was sold later in the year at double the price at harvest (Benson, 1997). Guaranteed prices, improvements in market access, and decentralization of bulk grain storage facilities are examples of structural and policy changes that can improve grain output prices accessed by farmers. For example, structural and policy support of farmer cooperatives can enable farmers enjoy lower fertilizer prices due to economies of scale, while at the same time improving their bargaining power when selling maize grain.

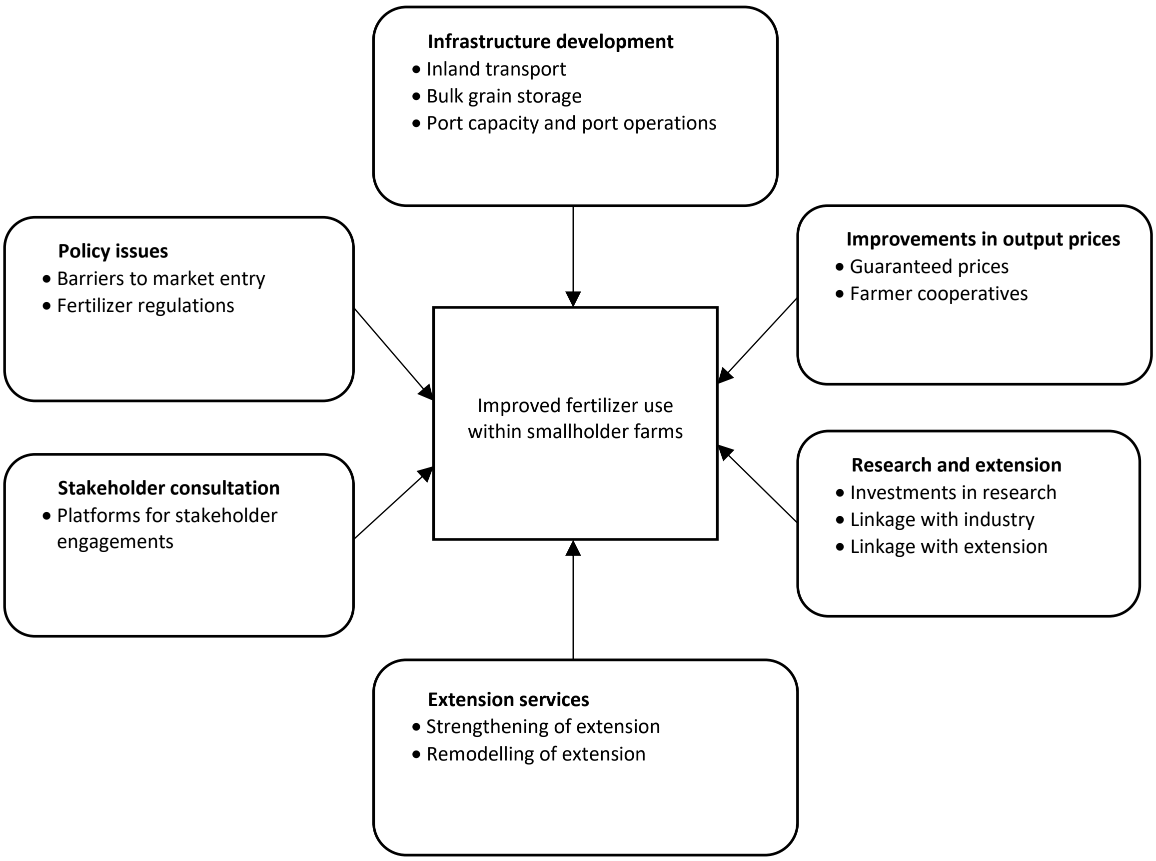

Fig. 6.4: A framework for a non-subsidy-based approach to improve fertilizer use in SSA.

Adediran, J. A. & Banjoko, V. A. (1995). Response of maize to nitrogen, phosphorus, and potassium fertilizers in the savanna zones of Nigeria. Communications in Soil Science and Plant Analysis 26(3-4): 593-606.

Africa Fertilizer Summit (2006). Africa fertilizer summit proceedings. IFDC, Muscle Shoals 182.

Africa Soil Information Service (AfSIS) website. http://africasoils.net/.

AGRA (2017). AGRA Annual Progress Report 2007 - 2016. Alliance for a Green Revolution in Africa (AGRA).

Anderson, J. M. & Ingram, J. S. I. (1994). Tropical Soil Biology and Fertility: A Handbook of Methods. Soil Science 157(4): 265.

Aune, J. B., Coulibaly, A. & Giller, K. E. (2017). Precision farming for increased land and labour productivity in semi-arid West Africa. A review. Agronomy for Sustainable Development 37(3): 16.

Balmford, A., Green, R. E. & Scharlemann, J. P. W. (2005). Sparing land for nature: Exploring the potential impact of changes in agricultural yield on the area needed for crop production. Global Change Biology 11(10): 1594-1605.

Baltzer, K. & Hansen, H. (2011). Agricultural input subsidies in Sub-Saharan Africa: Evaluation Study. Copenhagen, Denmark: Ministry of Foreign Affairs of Denmark.

Banful, A. B. (2011). Old Problems in the New Solutions? Politically Motivated Allocation of Program Benefits and the “New” Fertilizer Subsidies. World Development 39(7): 1166-1176.

Bates, D., Mächler, M., Bolker, B. & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. Journal of Statistical Software 67(1): 48.

Bationo, A., Hartemink, A., Lungu, O., Naimi, M., Okoth, P., Smaling, E., Thiombiano, L. & Waswa, B. (2012a). Knowing the African Soils to Improve Fertilizer Recommendations. In Improving Soil Fertility Recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT), 19-42 (Eds J. Kihara, D. Fatondji, J. W. Jones, G. Hoogenboom, R. Tabo and A. Bationo). Springer Netherlands.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B. & Kimetu, J. (2007). Soil organic carbon dynamics, functions and management in West African agro-ecosystems. Agricultural Systems 94(1): 13-25.

Bationo, A., Waswa, B., Abdou, A., Bado, B. V., Bonzi, M., Iwuafor, E., Kibunja, C., Kihara, J., Mucheru, M., Mugendi, D., Mugwe, J., Mwale, C., Okeyo, J., Olle, A., Roing, K. & Sedogo, M. (2012b).Overview of Long Term Experiments in Africa. In Lessons learned from Long-term Soil Fertility Management Experiments in Africa, 1-26 (Eds A. Bationo, B. Waswa, J. Kihara, I. Adolwa, B. Vanlauwe and K. Saidou). Dordrecht: Springer Netherlands.

Benson, T. D. (1997). Spatial and temporal variation in fertilizer recommendations for maize grown by smallholders in Malawi. In Maize Commodity Team Annual Report 1995/1996., 135-144 (Ed T. Benson). Lilongwe (Malawi). Department of Agricultural Research, Ministry of Agriculture and Irrigation, Chitedze Research Station.

Binswanger-Mkhize, H. P. (2017). African Agriculture Is Intensifying—But Not by Much. In Agriculture in Africa: Telling Myths from Facts, 95-103.

Bouyoucos, G. J. (1962). Hydrometer method improved for making particle size Analyses of soils. Agronomy Journal 54(5): 464-465.

Braun, A. R., Smaling, E. M. A., Muchugu, E. I., Shepherd, K. D. & Corbett, J. D. (1997). Maintenance and improvement of soil productivity in the highlands of Ethiopia, Kenya, Madagascar and Uganda. Nairobi, Kenya: African Highlands Initiative.

Brink, A. B. & Eva, H. D. (2009). Monitoring 25 years of land cover change dynamics in Africa: A sample based remote sensing approach. Applied Geography 29(4): 501-512.

Buresh, R. J. & Witt, C. (2007). Site-specific nutrient management. In Fertilizer Best Management Practices: General Principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations, 47 - 56 (Eds A. Krauss, K. Isherwood and P. Heffer). Paris: International Fertilizer Association.

Burke, W. J., Jayne, T. S. & Black, J. R. (2017). Factors explaining the low and variable profitability of fertilizer application to maize in Zambia. Agricultural Economics (United Kingdom) 48(1): 115-126.

Byerlee, D. R., Kelly, V. A., Kopicki, R. J. & Morris, M. (2007). Fertilizer Use in African Agriculture. The World Bank.

Carsky, R. J., Jagtap, S. S., Tian, G., Sanginga, N. & Vanlauwe, B. (1998). Maintenance of soil organic matter and N supply in the moist savanna zones of West Africa. In Soil Quality and Agricultural Sustainability 223-236 (Ed R. Lal). Chelsea, Michigan: Ann Arbor.

Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. Proceedings of the National Academy of Sciences 96(11): 5952-5959.

Castellanos-Navarrete, A., Tittonell, P., Rufino, M. C. & Giller, K. E. (2015). Feeding, crop residue and manure management for integrated soil fertility management. A case study from Kenya. Agricultural Systems 134: 24-35.

Chianu, J. N. & Mairura, F. (2012). Mineral fertilizers in the farming systems of sub-Saharan Africa. A review. Agronomy for Sustainable Development 32(2): 545-566.

Chianu, J., Adesina, A., Sanginga, P., Bationo, A. & Sanginga, N. (2011). Ex-ante Evaluation of the Impact of a Structural Change in Fertilizer Procurement Method in Sub-Saharan Africa. In Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts, 95-101 (Eds A. Bationo, B. Waswa, J. M. Okeyo, F. Maina and J. M. Kihara). Dordrecht: Springer Netherlands.

Chikowo, R., Zingore, S., Snapp, S. & Johnston, A. (2014). Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. Nutrient Cycling in Agroecosystems 100(1): 1-18.

Chuan, L., He, P., Pampolino, M. F., Johnston, A. M., Jin, J., Xu, X., Zhao, S., Qiu, S. & Zhou, W. (2013). Establishing a scientific basis for fertilizer recommendations for wheat in China: Yield response and agronomic efficiency. Field Crops Research 140: 1-8.

CIMMYT (1988). From agronomic data to farmer recommendations: an economics training manual. México, D.F., México: CIMMYT Economics Program.

Cisse, L. (2007). Balanced fertilization for sustainable use of plant nutrients. In Fertilizers Best Management Practices: General principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations. Papers presented at the IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium. 7-9 March 2007., 33 - 46 (Eds A. Krauss, K. Isherwood and P. Heffer). Paris: International Fertilizer Association.

Crawford, E., Jayne, T. & A. Kelly, V. (2005). Alternative Approaches for Promoting Fertilizer Use in Africa, with Particular Reference to the Role of Fertilizer Subsidies. Washington DC: World bank.

Deckers, J. (2002). A systems approach to target balanced nutrient management in soilscapes of sub-saharan Africa. In Integrated Plant Nutrient Management in Sub-Saharan Africa, 47-61 (Eds B. Vanlauwe, J. Diels, N. Sanginga and R. Merckx). Wallingford: CAB International.

de Wit, C. T. (1992). Resource use efficiency in agriculture. Agricultural Systems 40(1): 125-151.

Deininger, K., Savastano, S. & Xia, F. (2017). Smallholders' land access in Sub-Saharan Africa: A new landscape? Food Policy 67: 78-92.

Diao, X., Hazell, P. & Thurlow, J. (2010). The Role of Agriculture in African Development. World Development 38(10): 1375-1383.

Dobermann, A. (2007). Nutrient use efficiency - measurement and management. In Fertilizers Best Management Practices: General principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations. Papers presented at the IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium. 7-9 March 2007., 1-22 (Eds A. Kraus, K. Isherwood and P. Heffer). Paris: International Fertilizer Association.

Dongwen, L., Siva, G. & John, K. (2018). predictmeans: Calculate Predicted Means for Linear Models. R package version 1.0.1.

Ezui, K. S., Franke, A. C., Ahiabor, B. D. K., Tetteh, F. M., Sogbedji, J., Janssen, B. H., Mando, A. & Giller, K. E. (2017). Understanding cassava yield response to soil and fertilizer nutrient supply in West Africa. Plant and Soil 420(1-2): 331-347.

FAO (2018a). OECD-FAO Agricultural Outlook (Edition 2018).

FAO., IFAD., UNICEF., WFP. & WHO. (2018b). The state of Food Security and Nutrition in the World 2018. Building Climate Resilience for Food Security and Nutrition. Rome: FAO.

Fixen, P., Brentrup, F., Bruulsema, T., Garcia, F., Norton, R. & Zingore, S. (2015). Nutrient/fertilizer use efficiency: measurement, current situation and trends. 8-38.

Frelat, R., Lopez-Ridaura, S., Giller, K. E., Herrero, M., Douxchamps, S., Andersson Djurfeldt, A., Erenstein, O., Henderson, B., Kassie, M., Paul, B. K., Rigolot, C., Ritzema, R. S., Rodriguez, D., van Asten, P. J. & van Wijk, M. T. (2016). Drivers of household food availability in sub-Saharan Africa based on big data from small farms. Proceedings of the Natioal Academy of Science 113(2): 458-463.

Fridgen, J. J., Kitchen, N. R., Sudduth, K. A., Drummond, S. T., Wiebold, W. J. & Fraisse, C. W. (2004). Management Zone Analyst (MZA): Software for Subfield Management Zone Delineation. Agronomy Journal 96(1): 100-108.

Fryer, M. S., Slaton, N. A., Roberts, T. L. & Ross, W. J. (2019). Validation of soil-test-based phosphorus and potassium fertilizer recommendations for irrigated soybean. Soil Science Society of America Journal 83(3): 825-837.

FURP (1994). Fertilizer Use Recommendations. Fertilizer Use Recommendation Project., Vol. 1-24. Nairobi, Kenya: Kenya Agricultural Research Institute, National Agricultural Research Laboratories.

Giller, K. E., Cadisch, G., Ehaliotis, C., Adams, E., Sakala, W. D. & Mafongoya, P. L. (1997). Building Soil Nitrogen Capital in Africa. In Replenishing Soil Fertility in Africa, 151-192 Madison, WI: Soil Science Society of America and American Society of Agronomy.

Giller, K. E., Rowe, E. C., De Ridder, N. & Van Keulen, H. (2006). Resource use dynamics and interactions in the tropics: Scaling up in space and time. Agricultural Systems 88(1): 8-27.

Giller, K. E., Tittonell, P., Rufino, M. C., van Wijk, M. T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E. C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W. J., Sanogo, O. M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'Ungu, J., Mwale, M., Nwaga, D., Pacini, C. & Vanlauwe, B. (2011). Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. Agricultural Systems 104(2): 191-203.

Greenwood, D. J., Karpinets, T. V. & Stone, D. A. (2001). Dynamic model for the effects of soil P and fertilizer P on crop growth, P uptake and soil P in arable cropping: Model description. Annals of Botany 88(2): 279-291.

GYGA (2019). Global Yield Gap and Water Productivity Atlas [WWW Document]. Vol. 2019.

Haefele, S. M. & Wopereis, M. C. S. (2005). Spatial variability of indigenous supplies for N, P and K and its impact on fertilizer strategies for irrigated rice in West Africa. Plant and Soil 270(1): 57-72.

Hergert, G. W., Pan, W. L., Huggins, D. R., Grove, J. H. & Peck, T. R. (1997). Adequacy of current fertilizer recommendations for site-specific management. The state of site-specific management for agriculture: 283-300.

Heppell, J., Payvandi, S., Talboys, P., Zygalakis, K. C., Langton, D., Sylvester-Bradley, R., Edwards, A. C., Walker, R., Withers, P., Jones, D. L. & Roose, T. (2016). Use of a coupled soil-root-leaf model to optimise phosphate fertiliser use efficiency in barley. Plant and Soil 406(1-2): 341-357.

Houssou, N. & Zeller, M. (2011). To target or not to target? The costs, benefits, and impacts of indicator-based targeting. Food Policy 36(5): 627-637.

Ichami, S. M., Shepherd, K. D., Sila, A. M., Stoorvogel, J. J. & Hoffland, E. (2019). Fertilizer response and nitrogen use efficiency in African smallholder maize farms. Nutrient Cycling in Agroecosystems 113(1): 1-19.

Isaac, R. & Johnson, W. (1997). Elemental Determination By Inductively Coupled Plasma Atomic Emission Spectrometry. In Handbook of Reference Methods for Plant Analysis: CRC Press.

Janssen, B. H. (2011). Simple models and concepts as tools for the study of sustained soil productivity in long-term experiments. II. Crop nutrient equivalents, balanced supplies of available nutrients, and NPK triangles. Plant and Soil 339(1): 17-33.

Janssen, B. H., Guiking, F. C. T., van der Eijk, D., Smaling, E. M. A., Wolf, J. & van Reuler, H. (1990). A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46(4): 299-318.

Janssen, B. H., Lathwell, D. J. & Wolf, J. (1987). Modeling long-term crop response to fertilizer phosphorus. II. Comparison with field results. Agronomy Journal 79(3): 452-458.

Jayne, T. S., Mason, N. M., Burke, W. J. & Ariga, J. (2018). Review: Taking stock of Africa's second-generation agricultural input subsidy programs. Food Policy 75: 1-14.

Jayne, T. S. & Muyanga, M. (2012). Land constraints in Kenya's densely populated rural areas: implications for food policy and institutional reform. 4(3): 399-421.

Johnston, A. M. & Bruulsema, T. W. (2014). 4R Nutrient Stewardship for Improved Nutrient Use Efficiency. Procedia Engineering 83: 365-370.

Kamiri, W. M. H., Pypers, P. & Vanlauwe, B. (2011). Residual Effects of Applied Phosphorus Fertilizer on Maize Grain Yield and Phosphorus Recovery from a Long-Term Trial in Western Kenya. In Innovations as Key to the Green Revolution in Africa: Exploring the Scientific Facts, 717-727 (Eds A. Bationo, B. Waswa, M. J. Okeyo, F. Maina and M. J. Kihara). Dordrecht: Springer Netherlands.

KARI (1994). Fertilizer Use Recommendation Project (FURP). Vol. 12. Nairobi: Kenya Agricultural Research Institute, National Agricultural Research Laboratories.

Kifuko, M. N., Othieno, C. O., Okalebo, J. R., Kimenye, L. N., Ndung'u, K. W. & Kipkoech, A. K. (2007). Effect of combining organic residues with Minjingu phosphate rock on sorption and availability of phosphorus and maize production in acid soils of western Kenya. Experimental Agriculture 43(1): 51-66.

Kihanda, F. M., Warren, G. P. & Micheni, A. N. (2006). Effect of manure application on crop yield and soil chemical properties in a long-term field trial of semi-arid Kenya. Nutrient Cycling in Agroecosystems 76(2-3): 341-354.

Kihara, J., Huising, J., Nziguheba, G., Waswa, B. S., Njoroge, S., Kabambe, V., Iwuafor, E., Kibunja, C., Esilaba, A. O. & Coulibaly, A. (2015). Maize response to macronutrients and potential for profitability in sub-Saharan Africa. Nutrient Cycling in Agroecosystems: 171-181.

Kihara, J. & Njoroge, S. (2013). Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. Field Crops Research 150: 1-8.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C. & Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agriculture, Ecosystems & Environment 229: 1-12.

Kihara, J., Sileshi, G. W., Nziguheba, G., Kinyua, M., Zingore, S. & Sommer, R. (2017). Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. Agronomy for Sustainable Development 37(4): 25.

Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J. M., Chianu, J. & Bationo, A. (2010). Strategic phosphorus application in legume-cereal rotations increases land productivity and profitability in western Kenya. Experimental Agriculture 46(1): 35-52.

Koning, N. B. J., Van Ittersum, M. K., Becx, G. A., Van Boekel, M. A. J. S., Brandenburg, W. A., Van Den Broek, J. A., Goudriaan, J., Van Hofwegen, G., Jongeneel, R. A., Schiere, J. B. & Smies, M. (2008). Long-term global availability of food: continued abundance or new scarcity? NJAS - Wageningen Journal of Life Sciences 55(3): 229-292.

Krauss, A. (2007). Global assessment of the situation of fertilizer best management practices. In Fertilizers Best Management Practices: General principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations. Papers presented at the IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium. 7-9 March 2007., 231 - 238 (Eds A. Krauss, K. Isherwood and P. Heffer). Paris: International Fertilizer Association.

Kruse, J., Abraham, M., Amelung, W., Baum, C., Bol, R., Kühn, O., Lewandowski, H., Niederberger, J., Oelmann, Y., Rüger, C., Santner, J., Siebers, M., Siebers, N., Spohn, M., Vestergren, J., Vogts, A. & Leinweber, P. (2015). Innovative methods in soil phosphorus research: A review. Journal of Plant Nutrition and Soil Science 178(1): 43-88.

Kuria, A. W., Barrios, E., Pagella, T., Muthuri, C. W., Mukuralinda, A. & Sinclair, F. L. (2019). Farmers' knowledge of soil quality indicators along a land degradation gradient in Rwanda. Geoderma Regional 16: e00199.

Kurwakumire, N., Chikowo, R., Mtambanengwe, F., Mapfumo, P., Snapp, S., Johnston, A. & Zingore, S. (2014). Maize productivity and nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe. Field Crops Research 164(1): 136-147.

Kuznetsova, A., Brockhoff, P. B. & Christensen, R. H. B. (2017). lmerTest Package: Tests in Linear Mixed Effects Models. Journal of Statistical Software 82(13): 26.

Lobell, D. B. (2013). The use of satellite data for crop yield gap analysis. Field Crops Research 143(0): 56-64.

Lobell, D. B., Cassman, K. G. & Field, C. B. (2009). Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annual Review of Environment and Resources 34(1): 179-204.

Ma, Q., Tang, H., Rengel, Z. & Shen, J. (2013). Banding phosphorus and ammonium enhances nutrient uptake by maize via modifying root spatial distribution. Crop and Pasture Science 64(10): 965-975.

Madaras, M. & Koubová, M. (2015). Potassium availability and soil extraction tests in agricultural soils with low exchangeable potassium content. Plant, Soil and Environment 61(5): 234-239.

Mairura, F. S., Mugendi, D. N., Mwanje, J. I., Ramisch, J. J. & Mbugua, P. K. (2007). Assessment of farmers' perceptions of soil quality indicators within smallholder farms in the central highlands of Kenya. 1035-1046 Dordrecht: Springer Netherlands.

Mason, N. & Tembo, S. (2015). Do input Subsidies Reduce Poverty among Smallholder Farm Households? Panel Survey Evidence from Zambia. In International Association of Agricultural EconomistsMilan, Italy.

Marenya, P. P. & Barrett, C. B. (2009). Soil quality and fertilizer use rates among smallholder farmers in western Kenya. Agricultural Economics 40(5): 561-572.

Mason, N. M., Jayne, T. S. & van de Walle, N. (2016). The Political Economy of Fertilizer Subsidy Programs in Africa: Evidence from Zambia. American Journal of Agricultural Economics 99(3): 705-731.

Mason, N. M. & Smale, M. (2013). Impacts of subsidized hybrid seed on indicators of economic well-being among smallholder maize growers in Zambia. Agricultural Economics (United Kingdom) 44(6): 659-670.

Mather, D. L. & Jayne, T. S. (2018). Fertilizer subsidies and the role of targeting in crowding out: evidence from Kenya. Food Security: The Science, Sociology and Economics of Food Production and Access to Food: 397-417.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of Mehlich 2 extractant. Communications in Soil Science and Plant Analysis 15(12): 1409-1416.

Milbrow, S. (2017). rpart.plot: Plot 'rpart' Models: An Enhanced version of 'plot.rpart'.

Miller, R. & Horneck, D. (1997). Determination of Total Nitrogen in Plant Tissue. In Handbook of Reference Methods for Plant Analysis: CRC Press.

Minde, I. J., Jayne, T. S., Crawford, E. W., Ariga, J. & Govereh, J. (2008). Promoting Fertilizer Use in Africa: Current Issues and Empirical Evidence from Malawi, Zambia, and Kenya.

Minot, N. & Benson, T. (2009)."Fertilizer subsidies in Africa: Are Vouchers the Answer?". In IFPRI Issue Brief No 60. Washington, DC: International Food Policy Research Institute.

Morris, M., Kelly, V. A., Kopicki, R. J. & Byerlee, D. (2007). Fertilizer Use in African Agriculture. Washington DC: World Bank.

Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N. & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. Nature 490(7419): 254-257.

Muggeo, V. (2008). Segmented: An R Package to Fit Regression Models With Broken-Line Relationships. R News 8: 20-25.

Murage, E. W., Karanja, N. K., Smithson, P. C. & Woomer, P. L. (2000). Diagnostic indicators of soil quality in productive and non-productive smallholders' fields of Kenya's Central Highlands. Agriculture, Ecosystems and Environment 79(1): 1-8.

Murtagh, F. & Legendre, P. (2014). Ward's Hierarchical Agglomerative Clustering Method: Which Algorithms Implement Ward's Criterion? Journal of Classification 31(3): 274-295.

NAAIAP (2014). Soil Suitability Evaluation for Maize Production in Kenya. Nairobi: National Accelerated Agricultural Inputs Access Program.

Nezomba, H., Tauro, T. P., Mtambanengwe, F. & Mapfumo, P. (2010). Indigenous legume fallows (indifallows) as an alternative soil fertility resource in smallholder maize cropping systems. Field Crops Research 115(2): 149-157.

Njoroge, R., Otinga, A. N., Okalebo, J. R., Pepela, M. & Merckx, R. (2017a). Occurrence of poorly responsive soils in western Kenya and associated nutrient imbalances in maize (Zea mays L.). Field Crops Research 210: 162-174.

Njoroge, S., Schut, A. G. T., Giller, K. E. & Zingore, S. (2017b). Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. Field Crops Research 214(Supplement C): 321-330.

Njoroge, S., Schut, A. G. T., Giller, K. E. & Zingore, S. (2019). Learning from the soil's memory: Tailoring of fertilizer application based on past manure applications increases fertilizer use efficiency and crop productivity on Kenyan smallholder farms. European Journal of Agronomy 105: 52-61.

Nkamleu, G. B. (2011). Extensificantion versus Intensification: Revisiting the role of land in African agricultural growth. In African Economic ConferenceAddis Ababa, Ethiopia: Africa Development Bank.

Nyamangara, J., Makarimayi, E., Masvaya, E. N., Zingore, S. & Delve, R. J. (2011). Effect of soil fertility management strategies and resource-endowment on spatial soil fertility gradients, plant nutrient uptake and maize growth at two smallholder areas, North-Western Zimbabwe. South African Journal of Plant and Soil 28(1): 1-10.

Nziguheba, G., Palm, C. A., Berhe, T., Denning, G., Dicko, A., Diouf, O., Diru, W., Flor, R., Frimpong, F., Harawa, R., Kaya, B., Manumbu, E., McArthur, J., Mutuo, P., Ndiaye, M., Niang, A., Nkhoma, P., Nyadzi, G., Sachs, J., Sullivan, C., Teklu, G., Tobe, L. & Sanchez, P. A. (2010).The african green revolution. Results from the millennium villages project. In Advances in Agronomy, Vol. 109, 75-115.

Nziguheba, G., Merckx, R. & Palm, C. A. (2002). Soil phosphorus dynamics and maize response to different rates of phosphorus fertilizer applied to an Acrisol in western Kenya. Plant and Soil 243(1): 1-10.

Ojiem, J. O., de Ridder, N., Vanlauwe, B. & Giller, K. E. (2006). Socio-ecological niche: A conceptual framework for integration of legumes in smallholder farming systems. International Journal of Agricultural Sustainability 4(1): 79-93.

Okalebo, J. R., Gathua, K. W., Woomer, P. L., Tropical Soil, B. & Fertility, P. (1993). Laboratory methods of soil and plant analysis: a working manual. Nairobi: Tropical Soil Biology and Fertility Programme.

Olson, R. A., Anderson, F. N., Frank, K. D., Grabouski, P. H., G.W., R. & Shapiro, C. A. (1987). Soil testing interpretations: Sufficiency vs. build-up and maintenance. In Soil Testing: Sampling, Correlation, Calibration, and Interpretation (Ed J. R. Brown). Madison, WI: Soil Science Society of America.

Palm, C. A., Gachengo, C. N., Delve, R. J., Cadisch, G. & Giller, K. E. (2001). Organic inputs for soil fertility management in tropical agroecosystems: Application of an organic resource database. Agriculture, Ecosystems and Environment 83(1-2): 27-42.

Pampolino, M. F., Witt, C., Pasuquin, J. M., Johnston, A. & Fisher, M. J. (2012). Development approach and evaluation of the Nutrient Expert software for nutrient management in cereal crops. Computers and Electronics in Agriculture 88: 103-110.

Pan, L. & Christiaensen, L. (2012). Who is Vouching for the Input Voucher? Decentralized Targeting and Elite Capture in Tanzania. World Development 40(8): 1619-1633.

Pasuquin, J. M., Witt, C. & Pampolino, M. (2010). A new site-specific nutrient management approach for maize in the favorable tropical environments of Southeast Asia. In 19th World Congress of Soil Science, Soil Solutions for a Changing World. Brisbane, Australia.

Pathak, H., Aggarwal, P. K., Roetter, R., Kalra, N., Bandyopadhaya, S. K., Prasad, S. & Van Keulen, H. (2003). Modelling the quantitative evaluation of soil nutrient supply, nutrient use efficiency, and fertilizer requirements of wheat in India. Nutrient Cycling in Agroecosystems 65(2): 105-113.

Perez-Quezeda, J. F., Pettygrove, G. S. & Plant, R. E. (2003). Spatial-temporal analysis of yield and the influence of soil factors in two four-crop rotation fields in the Sacramento Valley, California. Agronomy 95: 676-687.

Place, F., Njuki, J., Murithi, F. & Mugo, F. (2006). Agricultural enterprise and land management in the highlands of Kenya. In Strategies for sustainable land management in the East African highlands, 190-216 (Eds Pender J, Place F and E. SJ). Washington, DC: International Food Policy Research Institute (IFPRI).

R Core Team (2017). R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing.

Reetz, H. F. (2016). Fertilizers and Their Efficient Use. Paris, France: International Fertilizer industry Association, IFA.

Ricker-Gilbert, J. & Jayne, T. S. (2017). Estimating the Enduring Effects of Fertiliser Subsidies on Commercial Fertiliser Demand and Maize Production: Panel Data Evidence from Malawi. Journal of agricultural economics 68(1): 70-97.

Robert, M. E. & Okalebo, J. R. (1992). Effects of phosphorus on the growth and development of maize. A search for strategies for sustainable dryland cropping in semi-arid eastern Kenya. ACIAR Proceedings 41: 55-62.

Robinson, J. B. D. (1993). Tropical Soil Biology and Fertility: A Handbook of Methods. Wallingford, Oxfordshire: CAB International.

Robinson, G. K. (1991). That BLUP is a Good Thing: The Estimation of Random Effects. Statistical Science 6(1): 15-32.

Ronner, E., Franke, A. C., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., Bala, A., van Heerwaarden, J. & Giller, K. E. (2016). Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. Field Crops Research 186: 133-145.

Rufino, M. C., Rowe, E. C., Delve, R. J. & Giller, K. E. (2006). Nitrogen cycling efficiencies through resource-poor African crop-livestock systems. Agriculture, Ecosystems and Environment 112(4): 261-282.

Rufino, M. C., Tittonell, P., van Wijk, M. T., Castellanos-Navarrete, A., Delve, R. J., de Ridder, N. & Giller, K. E. (2007). Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. Livestock Science 112(3): 273-287.

Rusinamhodzi, L., Corbeels, M., Zingore, S., Nyamangara, J. & Giller, K. E. (2013). Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. Field Crops Research 147: 40-53.

Ryan, J. (2007). What level of adaptation to local conditions is realistic in a developing country context? In Fertilizers Best Management Practices: General principles, Strategy for their Adoption and Voluntary Initiatives vs Regulations. Papers presented at the IFA International Workshop on Fertilizer Best Management Practices, Brussels, Belgium. 7-9 March 2007., 87 - 98 (Eds A. Krauss, K. Isherwood and P. Heffer). Paris: International Fertilizer Association.

Saïdou, A., Janssen, B. H. & Temminghoff, E. J. M. (2003). Effects of soil properties, mulch and NPK fertilizer on maize yields and nutrient budgets on ferralitic soils in southern Benin. Agriculture, Ecosystems and Environment 100(2-3): 265-273.

Sanchez, P. (2019). Phosphorus. In Properties and Management of Soils in the Tropics, 370-414 (Ed P. A. Sanchez). Cambridge: Cambridge University Press.

Sanchez, P., Palm, C., Sachs, J., Denning, G., Flor, R., Harawa, R., Jama, B., Kiflemariam, T., Konecky, B., Kozar, R., Lelerai, E., Malik, A., Modi, V., Mutuo, P., Niang, A., Okoth, H., Place, F., Sachs, S. E., Said, A., Siriri, D., Teklehaimanot, A., Wang, K., Wangila, J. & Zamba, C. (2007). The African millennium villages. Proceedings of the National Academy of Sciences of the United States of America 104(43): 16775-16780.

Sanchez, P. A. (2002). Soil Fertility and Hunger in Africa. Science 295(5562): 2019-2020.

Sanchez, P. A. (2018). Properties and Management of Soils in the Tropics. Cambridge: Cambridge University Press.

Sánchez, P. A. (2010). Tripling crop yields in tropical Africa. Nature Geoscience 3(5): 299-300.

Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Buresh, R. J., Izac, A. M. N., Mokwunye, A. U., Kwesiga, F. R., Ndiritu, C. G. & Woomer, P. L. (1997). Soil Fertility Replenishment in Africa: An Investment in Natural Resource Capital. In Replenishing Soil Fertility in Africa, 1-46 (Eds R. J. Buresh, P. A. Sanchez and F. Calhoun). Madison, WI: Soil Science Society of America and American Society of Agronomy.

Sanchez, P. A. & Palm, C. A. (1996). Nutrient cycling and agroforestry in Africa. Unasylva (185): 24-28.

Sanginga, N. & Woomer, P. L. (2009). Integrated Soil Fertility Management in Africa: Principles, Practices and Developmental Process. Nairobi: Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture.

Sattari, S. Z., Bouwman, A. F., Giller, K. E. & van Ittersum, M. K. (2012). Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proceedings of the National Academy of Sciences 109(16): 6348-6353.

Sattari, S. Z., van Ittersum, M. K., Bouwman, A. F., Smit, A. L. & Janssen, B. H. (2014). Crop yield response to soil fertility and N, P, K inputs in different environments: Testing and improving the QUEFTS model. Field Crops Research 157: 35-46.

Setiyono, T. D., Walters, D. T., Cassman, K. G., Witt, C. & Dobermann, A. (2010). Estimating maize nutrient uptake requirements. Field Crops Research 118(2): 158-168.

Shanahan, J. F., Schepers, J. S., Francis, D. D., Varvel, G. E., Wilhelm, W. W., Tringe, J. M., Schlemmer, M. R. & Major, D. J. (2001). Use of remote-sensing imagery to estimate corn grain yield. Agronomy Journal 93(3): 583-589.

Sheahan, M. & Barrett, C. B. (2014). Understanding the agricultural input landscape in Sub-Saharan Africa: recent plot, household, and community-level evidence. Washington, DC: World Bank Group.

Sheahan, M. & Barrett, C. B. (2017). Ten striking facts about agricultural input use in Sub-Saharan Africa. Food Policy 67: 12-25.

Shehu, B. M., Lawan, B. A., Jibrin, J. M., Kamara, A. Y., Mohammed, I. B., Rurinda, J., Zingore, S., Craufurd, P., Vanlauwe, B., Adam, A. M. & Merckx, R. (2019). Balanced nutrient requirements for maize in the Northern Nigerian Savanna: Parameterization and validation of QUEFTS model. Field Crops Research 241: 107585.

Shepherd, K., Ohlsson, E., R. Okalebo, J. & Ndufa, J. K. (1995). Potential impact of agroforestry on soil nutrient balances at the farm scale in the East African Highlands.

Shepherd, K. D. & Soule, M. J. (1998). Soil fertility management in west Kenya: Dynamic simulation of productivity, profitability and sustainability at different resource endowment levels. Agriculture, Ecosystems and Environment 71(1-3): 131-145.

Shiferaw, B., Prasanna, B. M., Hellin, J. & Bänziger, M. J. F. S. (2011). Crops that feed the world 6. Past successes and future challenges to the role played by maize in global food security. 3(3): 307.

Smaling, E. M. A. & Janssen, B. H. (1993). Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices. Geoderma 59(1-4): 21-44.

Smaling, E. M. A., Nandwa, S. M., Prestele, H., Roetter, R. & Muchena, F. N. (1992). Yield response of maize to fertilizers and manure under different agro-ecological conditions in Kenya. Agriculture, Ecosystems & Environment 41(3): 241-252.

Smaling, E. M. A., Stoorvogel, J. J. & Windmeijer, P. N. (1993). Calculating soil nutrient balances in Africa at different scales. Fertilizer Research 35(3): 237-250.

Smill, V. & Streatfeild, R. A. (2002). Enriching the earth: Fritz Haber, Carl Bosch, and the transformation of world food production.

Soule, M. J. & Shepherd, K. D. (2000). An ecological and economic analysis of phosphorus replenishment for Vihiga Division, western Kenya. Agricultural Systems 64(2): 83-98.

Steinberg, D. (2009). Chapter 10 CART: Classification and Regression Trees.

Stewart, M. W., Dibb, W. D., Johnston, A. E. & Smyth, T. (2005). The Contribution of Commercial Fertilizer Nutrients to Food Production. 97(1): 1-6.

Stoorvogel, J. & Smaling, E. (1990). Assessment of soil nutrient depletion in Sub-Saharan Africa: 1983 - 2000. Vol. 3: Literature review and description of land use systems.

Swift, M. J. & Shepherd, K. D. (2007). Saving Africa's soils: science and technology for improved soil management in Africa. Nairobi, Kenya.: World Agroforestry Centre.

Tan, Z. X., Lal, R. & Wiebe, K. D. (2005). Global soil nutrient depletion and yield reduction. Journal of Sustainable Agriculture 26(1): 123-146.

ten Berge, H. F. M., Hijbeek, R., van Loon, M. P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J. J., Boogaard, H. L., de Groot, H. L. E. & van Ittersum, M. K. (2019). Maize crop nutrient input requirements for food security in sub-Saharan Africa. Global Food Security 23: 9-21.

Therneau, T., Atkinson, B. & Ripley, B. (2017). rpart: Recursive Partitioning and Regression Trees.

Tilman, D., Balzer, C., Hill, J. & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 108(50): 20260-20264.

Tittonell, P., Corbeels, M., van Wijk, M. T. & Giller, K. E. (2010a). FIELD—A summary simulation model of the soil–crop system to analyse long-term resource interactions and use efficiencies at farm scale. European Journal of Agronomy 32(1): 10-21.

Tittonell, P. & Giller, K. E. (2013). When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. Field Crops Research 143(0): 76-90.

Tittonell, P., Muriuki, A., Klapwijk, C. J., Shepherd, K. D., Coe, R. & Vanlauwe, B. (2013). Soil Heterogeneity and Soil Fertility Gradients in Smallholder Farms of the East African Highlands. Soil Sci. Soc. Am. J. 77(2): 525-538.

Tittonell, P., Rufino, M. C., Janssen, B. H. & Giller, K. E. (2010b). Carbon and nutrient losses during manure storage under traditional and improved practices in smallholder crop-livestock systems—evidence from Kenya. Plant and Soil 328(1): 253-269.

Tittonell, P., Shepherd, K. D., Vanlauwe, B. & Giller, K. E. (2008a). Unravelling the effects of soil and crop management on maize productivity in smallholder agricultural systems of western Kenya-An application of classification and regression tree analysis. Agriculture, Ecosystems and Environment 123(1-3): 137-150.

Tittonell, P., Vanlauwe, B., Corbeels, M. & Giller, K. E. (2008b). Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant and Soil 313(1-2): 19-37.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Rowe, E. C. & Giller, K. E. (2005a). Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agriculture, Ecosystems and Environment 110(3-4): 149-165.

Tittonell, P., Vanlauwe, B., Leffelaar, P. A., Shepherd, K. D. & Giller, K. E. (2005b). Exploring diversity in soil fertility management of smallholder farms in western Kenya: II. Within-farm variability in resource allocation, nutrient flows and soil fertility status. Agriculture, Ecosystems and Environment 110(3-4): 166-184.

Tully, K. L., Wood, S. A., Almaraz, M., Neill, C. & Palm, C. (2015). The effect of mineral and organic nutrient input on yields and nitrogen balances in western Kenya. Agriculture, Ecosystems and Environment 214: 10-20.

UN (2015). Transforming our World: the 2030 Agenda for Sustainable Development. Resolution adopted by the General Assembly on 25 September 2015. United Nations.

Van der Eijk, D. (1997). Phosphate fixation and the response of maize to fertilizer phosphate in Kenyan soils. Vol. PhD Netherlands: Wageningen University.

Van der Eijk, D., Janssen, B. H. & Oenema, O. (2006). Initial and residual effects of fertilizer phosphorus on soil phosphorus and maize yields on phosphorus fixing soils. A case study in south-west Kenya. Agriculture, Ecosystems and Environment 116(1-2): 104-120.

Van Ittersum, M. K. & Cassman, K. G. (2013). Yield gap analysis—Rationale, methods and applications—Introduction to the Special Issue. Field Crops Research 143(0): 1-3.

Van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P. & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. Field Crops Research 143(0): 4-17.

Van Ittersum, M. K. & Rabbinge, R. (1997). Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Research 52(3): 197-208.

Van Ittersum, M. K., Van Bussel, L. G. J., Wolf, J., Grassini, P., Van Wart, J., Guilpart, N., Claessens, L., De Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., Van Oort, P. A. J., Van Loon, M. P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J. H. J. R., Ouattara, K., Tesfaye, K. & Cassman, K. G. (2016). Can sub-Saharan Africa feed itself? Proceedings of the National Academy of Sciences of the United States of America 113(52): 14964-14969.

Van Keulen, H. & Breman, H. (1990). Agricultural development in the West African Sahelian region: a cure against land hunger? Agriculture, Ecosystems and Environment 32(3-4): 177-197.

Van Noordwijk, M. & Cadisch, G. (2002). Access and excess problems in plant nutrition. Plant and Soil 247: 25-39.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K. E., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K. D., Smaling, E. M. A., Woomer, P. L. & Sanginga, N. (2010). Integrated soil fertility management: Operational definition and consequences for implementation and dissemination. Outlook on Agriculture 39(1): 17-24.

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J. & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. SOIL 1(1): 491-508.

Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R. & Six, J. (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. Plant and Soil 339(1): 35-50.

Vanlauwe, B., Tittonell, P. & Mukalama, J. (2006). Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutrient Cycling in Agroecosystems 76(2-3): 171-182.

Vanlauwe, B., Sanginga, N., Giller, K. E. & Merckx, R. (2004). Management of Nitrogen Fertilizer in Maize-based Systems in Subhumid Areas of Sub-Saharan Africa. In Agriculture and the Nitrogen cycle: Assessing the impacts of Fertilizer Use on Food Production and the Environment, 115-127 (Eds A. R. Mosier, J. K. Syers and J. R. Freney).

Vanlauwe, B., A. Palm, C., K. Murwira, H. & Merckx, R. (2002). Organic resource management in sub-Saharan Africa: Validation of a residue quality-driven decision support system. Agronomie 22: 839-846.

Vlek, P. L. G. (1990). The role of fertilizers in sustaining agriculture in sub-Saharan Africa. Fertilizer Research 26(1): 327-339.

Voss, R. (1998). Fertility recommendations: Past and present. Communications in Soil Science and Plant Analysis 29(11-14): 1429-1440.

Wang, M., Zheng, Q., Shen, Q. & Guo, S. (2013). The critical role of potassium in plant stress response. International Journal of Molecular Sciences 14(4): 7370-7390.

Wolf, J., De Wit, C., Janssen, B. & Lathwell, D. (1987). Modelling long-term crop response to fertilizer phosphorus. I. The model. Agronomy Journal 79: 445-451.

Wopereis, M. C. S., Tamélokpo, A., Ezui, K., Gnakpénou, D., Fofana, B. & Breman, H. (2006). Mineral fertilizer management of maize on farmer fields differing in organic inputs in the West African savanna. Field Crops Research 96(2-3): 355-362.

Xu, X., He, P., Qiu, S., Pampolino, M. F., Zhao, S., Johnston, A. M. & Zhou, W. (2014). Estimating a new approach of fertilizer recommendation across small-holder farms in China. Field Crops Research 163: 10-17.

Xu, X., Liu, X., He, P., Johnston, A. M., Zhao, S., Qiu, S. & Zhou, W. (2015). Yield gap, indigenous nutrient supply and nutrient use efficiency for maize in China. PLoS ONE 10(10): 1-12.

Xu, Z., Guan, Z., Jayne, T. S. & Black, R. (2009). Factors influencing the profitability of fertilizer use on maize in Zambia. Agricultural Economics 40(4): 437-446.

Yang, F., Xu, X., Wang, W., Wang, J., Wei, D., He, P., Pampolino, M. F. & Johnston, A. M. (2017). Estimating nutrient uptake requirements for soybean using QUEFTS model in China. PLoS ONE 12(5).

Zhang, H., Wei, X., Zou, T., Li, Z. & Yang, G. (2015). Agriculture Big Data: Research Status, Challenges and Countermeasures. In Computer and Computing Technologies in Agriculture VIII. CCTA 2014. IFIP Advances in Information and Communication Technology, 137-143 (Eds D. Li and Y. Chen). Cham: Springer International Publishing.

Zingore, S., Delve, R., Nyamangara, J. & Giller, K. (2008). Multiple benefits of manure: The key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. Nutrient Cycling in Agroecosystems 80(3): 267-282.

Zingore, S., Murwira, H. K., Delve, R. J. & Giller, K. E. (2007a). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on smallholder farms in Zimbabwe. Agriculture, Ecosystems & Environment 119(1–2): 112-126.

Zingore, S., Murwira, H. K., Delve, R. J. & Giller, K. E. (2007b). Soil type, management history and current resource allocation: Three dimensions regulating variability in crop productivity on African smallholder farms. Field Crops Research 101(3): 296-305.

Zingore, S., Tittonell, P., Corbeels, M., van Wijk, M. T. & Giller, K. E. (2011). Managing soil fertility diversity to enhance resource use efficiencies in smallholder farming systems: a case from Murewa District, Zimbabwe. Nutrient Cycling in Agroecosystems 90(1): 87-103.

Zörb, C., Senbayram, M. & Peiter, E. (2014). Potassium in agriculture – Status and perspectives. Journal of Plant Physiology 171(9): 656-669.

Annex A: Improving maize yield response predictions to fertilizer applications in the QUEFTS model.

Annex B: Feed the crop, not the soil: Regenerating crop productivity on nutrient depleted soils in western Kenya.

Annex A

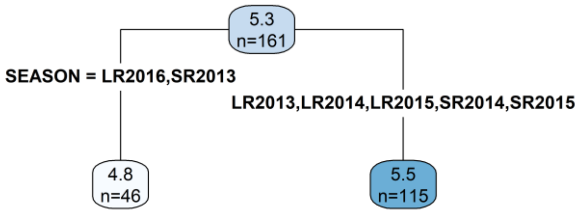

Fig. A1: CART diagram showing differences in mean maize yield (t ha^{-1}, 88% DM) response to NPK fertilization between good and poor seasons.

Relationship between BLUP estimated and measured values

The relationship between measured and BLUP estimates illustrated measurement errors not related to differences in fields or treatments imposed in key soil properties and total N, P and K uptake (Fig. A2). Measurement errors were minimal for SOC with a general good agreement between measured and BLUP values (Fig. A2a). Smaller R^2 values and large residuals indicated stronger effects of measurement errors particularly for P-Olsen and total K uptake (Fig. A2b & A2f).

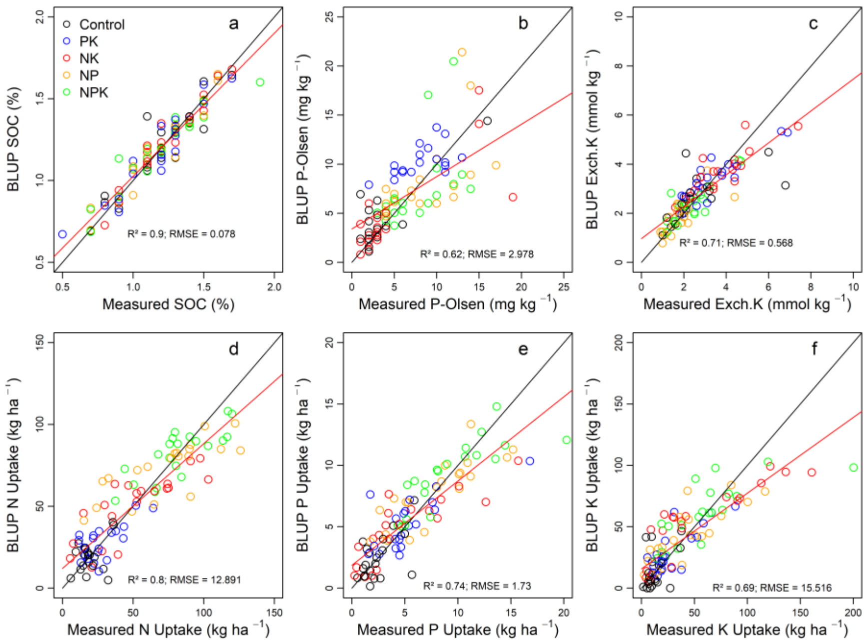

Fig. A2: Relationship between measured and BLUP estimated: a) soil organic C; b) P Olsen; c) exchangeable K; d) total N uptake; e) total P uptake; and, f) total K uptake. Black lines are 1:1 line, while red lines are fitted lines.

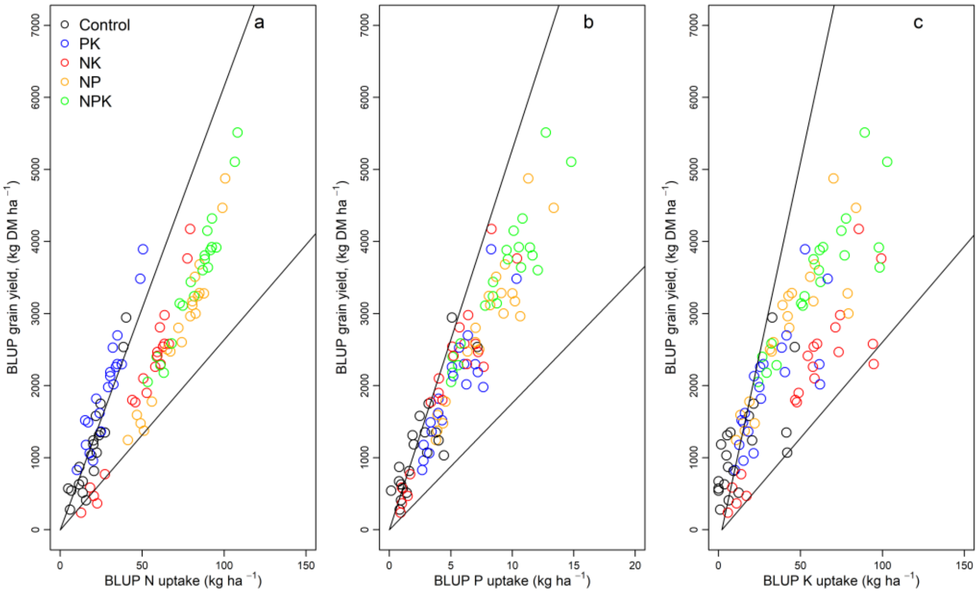

Fig. A3: Relationship between maize grain yield and: a) total N uptake; b) total P uptake c) total K uptake in the seventh consecutive season of on-farm nutrient omission trials (n = 23) in Sidindi, western Kenya. Upper and lower lines are maximum nutrient dilution and maximum nutrient accumulation lines respectively based on the default QUEFTS model.

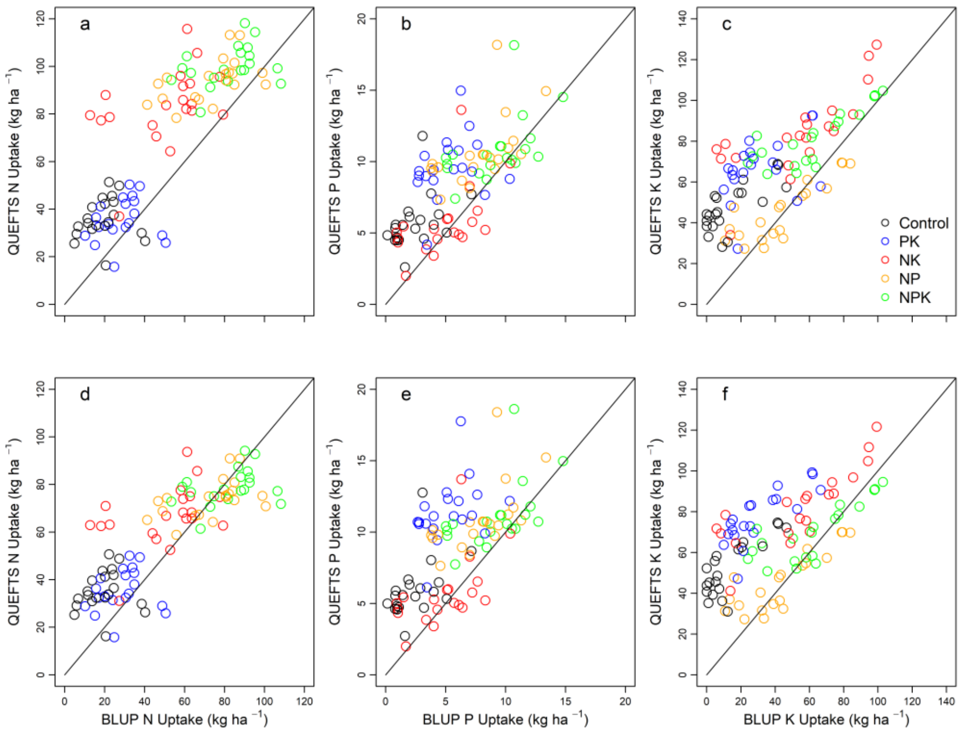

Fig. A4: Relationship between QUEFTS and BLUP estimated total N, P and K uptake with default (a – c), and calibrated (d – f) N, P and K maximum accumulation and dilution, and recovery values.

Relationship between soil chemical properties and control yield with nutrient uptake from the soil

Potential soil N, P and K supply in the QUEFTS model is based on SOC, P-Olsen, and exchangeable K respectively. Crop N, P and K uptake in PK, NK and NP treatment plots should therefore closely correlate with SOC, P-Olsen, and exchangeable K contents respectively. BLUP total N and P uptake were however poorly related to BLUP estimates of SOC and P-Olsen respectively (Fig. A5b & A5d), suggesting that SOC and P-Olsen were poorly informative of potentials soil N and P supply in the default QUEFTS model. On the contrary, grain yield in the control treatment plot was indicative of N, P and K uptake in the PK, NK and NP treatment plots respectively (Fig. A5a, A5c & A5e), illustrating that unfertilized yield may be a better predictor of potential soil N, P and K supply.

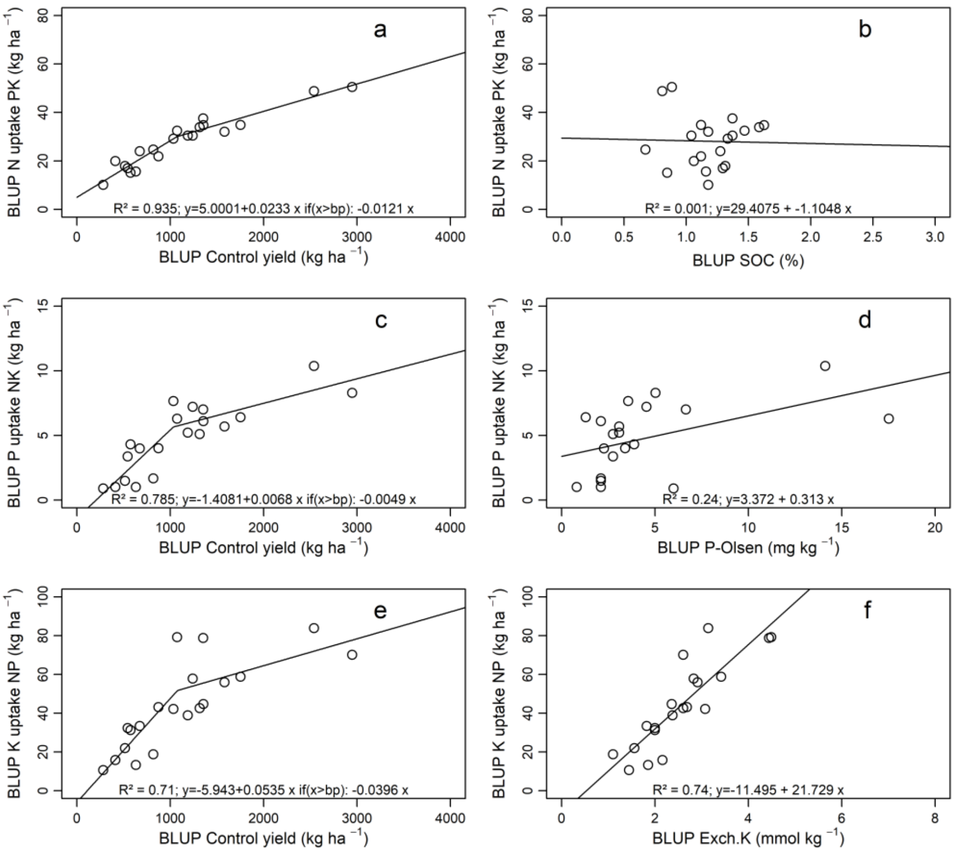

Fig. A5: Relationship between: BLUP estimates of total N uptake in PK plots and a) BLUP yield estimates in control plots, and b) BLUP soil organic C estimates in PK plots; BLUP estimates of total P uptake in NK plots and c) BLUP yield estimates in control plots, and d) BLUP P-Olsen estimates in NK plots; and, BLUP estimates of total K uptake in NP plots and e) BLUP yield estimate in control plots, and f) BLUP soil exchangeable K estimates in NP plots.

Annex B

The RC-P Model

Model input data and model parameters

Data required to run the RC-P model are the: (i) rate and type of fertilizer applied; (ii) the total crop uptake of P by the unfertilized crop and that by the fertilized crop during the first year after fertilizer application; the (iii) net input of P; and the (iv) time constants of transfer between the labile and the stable pools. Table B1 shows the model input data used and the calculation of the various model parameters as previously reported by Wolf *et al.* (1987). Data on rate, fertilizer type, and total P uptake were derived from the last season of the Phase 1 (nutrient omission trial). P uptake from the NK and NPK treatments represented P uptake in the unfertilized and fertilized crop respectively.

Table B1: Input data, calculation of model parameters, and initial pool sizes for an unfertilized and fertilized soil. Adapted from (Wolf *et al.*, 1987).

Line number	Description	Calculation*	Value±
	Input data		
1	Type of fertilizer		Triple superphosphate
2	Rate		40
3	P uptake from unfertilized soil		Uptake in NK plot
4	P uptake from fertilized soil		Uptake in NPK plot
5	Net input of P		0
6	Time constant of P transfer from labile to stable pool, years		5
7	Time constant of P transfer from stable to labile pool, years		30
	Model parameters		
8	Labile fraction of fertilizer P		0.8
9	Stable fraction of fertilizer P		0.2
10	Labile P from fertilizer	2 x 8	32
11	Stable P from fertilizer	2 x 9	8
12	First season recovery	4 - 3	8
13	Uptake fraction of labile pool		0.04
	Initial situation		
14	Size of labile pool, US‡	3 ÷ 13	
15	Transfer labile to stable, US	14 ÷ 6	
16	Transfer stable to labile, US	3 + 15	
17	Size of stable pool, US	7 x 16	
18	Size of labile pool, FS	10 + 14	
19	Size of stable pool, FS	11 + 17	

*Numbers refer to line numbers
±Sizes of pools are expressed in kg P ha^{-1}; fractions in kg P ha^{-1}; net input, transfers, changes, and P uptake and recovery in kg P ha^{-1} s^{-1}; and time constants in years.
‡US = unfertilized soil; FS = fertilized soil.

Determination of initial P pool sizes

Data on total P uptake in fertilized and unfertilized soils was only available for the last season of Phase 1. To determine initial labile and stable P pools in each field at the start of phase one of the experiment, we used measured P uptake data in the seventh season in treatment plots with and without P applied (NPK and NK treatment plots respectively) to first determine sizes of labile and stable P pools in this seventh season. Using these values, the RC-P model was back cast for six seasons to predict initial labile and stable P pools in each field at the start of Phase 1 in LR 2013. Using these initial values, the model was then run to predict seasonal P uptake in plots with and without fertilizer P applied over the course of the study period.

Accounting for direct uptake of placed fertilizer P

In the original RC-P model, P uptake by plants is assumed to be only from the labile P pool (Wolf *et al.,* 1987). Plant P uptake following fertilizer P application is therefore based on the contribution of applied fertilizer P to the labile P pool. This is calculated as a function of the fertilizer P applied, and the labile P fraction of the fertilizer P applied (Wolf *et al.,* 1987). P in this labile pool has an availability to crops equal to that of the labile fraction of broadcast fertilizer (Wolf *et al.,* 1987). Maize yield response to P application in the P exhausted soils however pointed at larger recovery of applied fertilizer P (Table 5.3 Chapter 5). This was consistent with findings by Van der Eijk *et al.* (2006) who reported larger recovery of placed versus broadcast fertilizer P in strongly P exhausted soils. This has been related to the presence of pockets of enriched soils with high P concentration directly below the placed fertilizer, allowing P uptake to proceed at a higher rate than that from the labile pool (Van der Eijk *et al.,* 2006). This indicates a possible bypass in P uptake where plants take up P directly from the placed fertilizer, as opposed to uptake from only the labile pool.

Estimation of P uptake in nutrient exhausted soils

Total P uptake in P exhausted soils was only measured after the third season of fertilizer P application in nutrient exhausted soils. To assess total P uptake in the first seasons of fertilizer P application in these exhausted soils, we estimated total P uptake based on the observed relationship between yield and total P uptake at the end of Phase 1. The relationship between yield and total P uptake at the end of phase one indicated a curvilinear relationship with larger total P uptake at high yields (Fig. B1). Based on this relationship, we used observed yield values in the three cropping seasons of Phase 2-NOT to estimate total P uptake following fertilizer P application in treatment plots with P previously omitted.

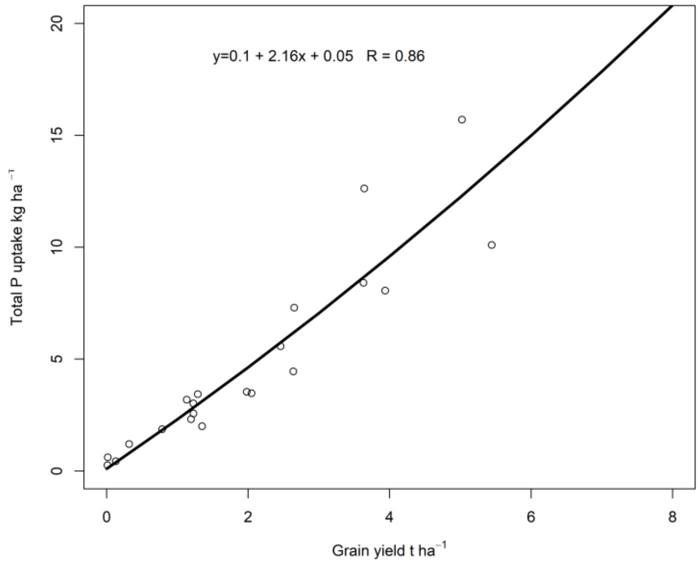

Fig. B1: Relationship between yield and total P uptake in the last season of experimental phase one.

Modelling P uptake in nutrient exhausted fields

Modelling of total P uptake in P exhausted soils was assessed by modelling total P uptake patterns following fertilizer P application in the former NK treatment plots in experimental Phase 2-NOT. Labile and stable P pool sizes in soils with and without fertilizer P applied at the end of Phase 1 of the experiment served as the initial soil P pools for modelling of P uptake in P. Prediction of total P uptake was first conducted using the original model parameters and equations (Table B1). The modified model accounted for direct uptake of placed fertilizer P by introducing a new parameter that represented the direct uptake of placed fertilizer P. Based on an estimated total P uptake of 10 kg P ha^{-1} in the first cropping season in soils with exhausted P stocks (Fig. 5.6 Chapter 5), recovery of the applied 40 kg P ha^{-1} was estimated at 30% given a labile P fraction of 0.8 for the applied TSP fertilizer (Table B1). The new parameter value representing direct uptake of placed fertilizer was therefore set at 0.3.

Agriculture in sub-Saharan Africa (SSA) is characterized by smallholder farming systems with low crop productivity. This is largely a result of soil fertility depletion following continuous cropping with minimal nutrient replenishment. To sustainably intensify crop productivity, increased mineral fertilizer use is required to address nutrient deficiencies that currently limit crop productivity. Current fertilizer use in smallholder farming systems of SSA is however characterized by large differences in crop yields with strong, but poorly understood variability in crop yield responses to applied mineral fertilizers. This is linked to crop management and strong heterogeneity in soil fertility between and within farms. For substantial increases in crop productivity with minimal costs for the farmer, better fertilizer recommendations that account for local soil fertility is required. This demands an improved understanding of dynamic patterns of crop yield responses, and the identification of key factors determining the variation in crop yield responses at the farm level. The key aim of this thesis was therefore to quantify and explain patterns of crop yields and yield responses to fertilizer applications in these heterogenous smallholder farming systems of SSA through detailed on-farm studies in western Kenya.

In Chapter 2, dynamic and changing patterns of maize yield responses to fertilizer N, P and K applications were studied. In this chapter, results from on-farm nutrient omission experiments repeated during six consecutive seasons in the same trial locations were used to assess changes in the frequency and magnitude of maize yield response to fertilizer application. Treatments included a control (no nutrients applied), PK, NK, NP and NPK, and were established on 23 farms without replication. The frequency and magnitude of maize yield response to fertilizer applications varied strongly between farms and cropping seasons. Within six cropping seasons, the proportion of fields strongly responsive to N, P and K applications increased from 29 to 96%, 4 to 43%, and 4 to 30%, respectively. While the proportion of fields that were strongly responsive to K was relatively small, yield losses of up to 80% were observed on these farms. Observed yield response patterns were not adequately captured by soil analysis data, suggesting the need for an additional characterization of farms to better explain observed yield response patterns. Based on consistently high yields and minimal variability in the maize yield response observed in the NPK treatment, we concluded that differences in N, P, and K fertility caused the spatial variability and fertilization with NPK reduced the observed spatial-temporal variability.

Guided by findings in Chapter 2, Chapter 3 aimed at assessing and quantifying key factors causing variability in maize yield response to fertilizer N, P and K applications.

Past animal manure application was identified as the key factor causing the strong spatial variation in maize yield response to fertilizer applications. Mean maize yield response to N, P and K application was 2.8, 1.1 and 0.6 t ha^{-1} in farms with past manure applications, and 2.3, 3.0 and 1.6 t ha^{-1} in farms without past manure applications. Differences in maize yield response in fields with and without past manure applications were mainly related to enhanced soil P and K supply, and a larger recovery of applied N in fields where manure was applied in the past. In the seventh season of consecutive nutrient omission trials, past manure application contributed a fertilizer equivalent of 28.3, 29.8 and 31.5 kg ha^{-1} of N, P and K respectively. Findings from this chapter illustrated that accounting for past farm management helps to explain observed yield response patterns. These findings further indicated that the strong influence of past animal manure application on yield response to fertilizer application merits the inclusion of past manure application as a co-variate in analysis of yield response data from smallholder cropping systems of SSA to reduce the unexplained spatial variability.

In Chapter 4, we assessed the accuracy of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model in predicting maize grain yield following balanced and imbalanced fertilization under variable soil fertility conditions. The QUEFTS model did not adequately predict maize grain yield responses, mainly due to limitations in estimates of soil nutrient supply based on soil analysis data. Modified relationships for soil nutrient supply based on yields in unfertilized control treatment plots provided improved estimates of in particular soil N and P supply. This resulted in improved yield response predictions with the QUEFTS model. This study highlighted strengths and limitations in the current QUEFTS model in adequately predicting maize yield response to fertilizer applications under highly variable soil fertility conditions that are characteristic of SSA. Actual maize yields on farmer fields under minimal or no fertilization proved a useful proxy for soil nutrient supply in decision support tools, assuming that nutrient contents are reasonably constant and control yield is determined by limitations in soil nutrient supply. This presents a cost-effective yet fairly robust pathway for improving predictions of maize yield response to fertilizer applications at the farm level.

Chapter 5 aimed at providing insights on response to fertilization on strongly nutrient depleted soils in Siaya. In this study, balanced NPK treatments and omission treatments were established in former nutrient omission trial plots. This study used the RC-P model to assess patterns of short- and long-term fertilizer P recovery under a range of soil fertility conditions. Soils with strongly depleted nutrient stocks were strongly responsive to balanced NPK application. Mean maize grain yields in the second season of combined NPK application on these soils were 5.5, 6.7, 6.5 and 7.0 t ha^{-1} at 88% dry matter in the former control, PK, NK and NP treatment plots respectively, compared to 7.5 t ha^{-1} in the long-term NPK treatment plots. Findings from this study demonstrated that even strongly nutrient depleted soils of western Kenya are responsive to balanced NPK applications, and no prior investments to rebuild nutrient stocks and organic matter are required on these clay-rich soils for crop yields to be increased. Placed fertilizer strongly improved P recovery. Accounting for direct uptake of placed fertilizer P in the RC-P model resulted in improved model predictions of fertilizer P recovery. As all fields were responsive to NPK, even when strongly depleted, there is no direct need to focus on increasing soil fertility. It was concluded that for crop productivity intensification on these strongly nutrient depleted soils of Siaya, efforts should be aimed at fertilizing the crop, where soil nutrient stocks will recover slowly over time without additional farmer investments.

In chapter 6, findings from Chapter 2 to 5 were integrated to provide insights for sustainable maize productivity intensification in smallholder farms of SSA based on fertilizer use. It was discussed that regular applications of mineral P and K fertilizers that meet crop nutrient demands are a more sustainable approach than a one-off large application of P and K fertilizers to improve the fertility of strongly depleted soils. In this chapter, options for optimization of fertilizer use efficiency based on integrated soil fertility management (ISFM) were also explored. It was found that fertilizer use efficiency can be enhanced through assessment of crop yield response patterns and animal manure application patterns at the farm level. We concluded that adjustments of fertilizer P and K application rates based on past animal manure application history, and the co-application of fertilizer N with available high-quality organic resources is required to optimize N, P and K fertilizer use efficiency at the field level.

This thesis provides an improved understanding of the yield variability, and magnitude and drivers of variation in maize yield responses to fertilizer applications in smallholder farming systems of SSA. Findings from this thesis provide a means for improved targeting of fertilizer applications, resulting in better prediction of crop yield and yield responses to applied fertilizer. Findings in this thesis also demonstrate that mean yields of 4.5 t ha^{-1}, required for maize self-sufficiency in the East African region, are achievable despite strong heterogeneity between fields and farms once fertilization and field management is right.

Landbouw ten zuiden van de Sahara wordt gekarakteriseerd door landbouwsystemen met kleine boeren en een lage productiviteit. Dit wordt voor een groot deel veroorzaakt door een sterk verslechterde bodemvruchtbaarheid als gevolg van continu-teelt zonder compenserende bemesting waardoor verlies van nutriënten-leverend vermogen optreedt door uitmijning. Duurzame intensivering vereist een verhoogde minerale bemesting om deze nutriënt-deficiënties te adresseren die nu de gewasproductiviteit sterk beperken. Landbouwsystemen met kleine boeren wordt gekarakteriseerd door grote verschillen in opbrengsten en een grote variabiliteit in de toename van productiviteit als er wordt bemest met kunstmest. Deze variabiliteit wordt nog slecht begrepen, maar is waarschijnlijk gekoppeld aan de grote verschillen in management van gewassen en de grote heterogeniteit in bodemvruchtbaarheid tussen bedrijven en tussen percelen binnen een bedrijf. Voor een substantiële toename in gewasproductiviteit met minimale kosten voor de boer zijn betere bemestingsadviezen nodig die rekening houden met de lokale bodemvruchtbaarheid. Het hoofddoel van dit proefschrift was om de patronen in bodemvruchtbaarheid ten zuiden van de Sahara in de betreffende bedrijfssystemen te kwantificeren en verklaren met gedetailleerde studies op boerenbedrijven in het westen van Kenia.

In hoofdstuk 2 zijn dynamische patronen van de opbrengstrespons van maïs door N, P en K giften bestudeerd. De resultaten van 6 opeenvolgende seizoenen van zogenaamde nutriënt-omissieproeven in Siaya (west-Kenia) met behandelingen op de zelfde plek zijn gebruikt om veranderingen in de magnitude en frequentieverdeling van de opbrengstrespons van maïs op bemestingen te bepalen. De proef is bij 23 bedrijven gestart, waarbij op elk bedrijf vijf behandelingen werden aangelegd, zonder herhaling, met een controle zonder bemesting en behandelingen met respectievelijk PK, NK, NP en NPK bemestingen. De respons varieerde sterk tussen de bedrijven waarbij de frequentieverdeling van responsen ook sterk veranderden in de loop van de jaren. Het aandeel van bedrijven met een sterke respons op bemesting nam toe van 29 tot 96% voor N, 4 tot 43 % voor P en 4 tot 30% voor K. Alhoewel het aandeel van bedrijven met een sterke respons op K relatief klein was, werden op deze bedrijven opbrengstdervingen tot 80% gemeten. De geobserveerde opbrengstpatronen werden niet adequaat beschreven door analyses van grondmonsters, wat vraagt om een additionele karakterisering van deze bedrijven om de beschreven patronen beter te kunnen verklaren. De sterke, consistente en weinig variabele opbrengstrespons van de NPK behandeling die in de proeven werden gemeten leidde tot de conclusie dat de elementen N, P en K de belangrijkste factoren zijn en dat NPK bemesting de beschreven variatie in ruimte en tijd sterk verkleint.

Geleid door de bevindingen uit hoofdstuk 2, had hoofdstuk 3 als doel om sleutelfactoren te identificeren en de invloed op de variabiliteit in opbrengstrespons te kwantificeren. Bemesting met dierlijke mest in het verleden was de belangrijkste variabele waarmee de variabiliteit in respons verklaard kon worden. De opbrengstrespons van maïs door bemestingen was 2,8 t/ha voor N, 1,1 t/ha voor P en 0,6 t/ha voor K op bedrijven waar dierlijke mest was gebruikt en 2,3 t/ha voor N, 3,0 t/ha voor P en 1,6 t/ha voor K op bedrijven waar geen dierlijke mest was gebruikt in het verleden. Dit geeft het belang van dierlijke mest voor met name de P en K beschikbaarheid in de bodem aan. In het zevende seizoen na de laatste dierlijke mestgift was de equivalente kunstmestgift gelijk aan 28,3 kg N/ha, 29,8 kg P/ha en 31,5 kg K/ha. Deze bevindingen laten zien dat mestgiften in het verleden een belangrijk deel van de patronen in opbrengsten en opbrengstrespons kunnen verklaren. Dit laat ook zien dat bemestingsproeven waarbij verschillende locaties worden gecombineerd beter geanalyseerd kunnen worden als mestgiften in het verleden wordt meegenomen. Dit is met name van belang om de respons op P en K op percelen zonder gebruik van dierlijke mest te kunnen ontwarren van de achtergrondruis door de ruimtelijke variatiecomponent, wat zal leiden tot een beter begrip van landbouwsystemen met kleine boeren ten zuiden van de Sahara.

In hoofdstuk 4 is de voorspelfout van het QUEFTS model voor maïsopbrengst in respons op gebalanceerde en ongebalanceerde bemesting op velden met een variabele bodemvruchtbaarheid beoordeeld. Het QUEFTS model gaf geen nauwkeurige voorspelling van de opbrengstrespons, vooral door een gebrekkige schatting van de beschikbare nutriënten die in de bodem beschikbaar zijn. De voorspelde opbrengstrespons verbeterde sterk als de nutriëntenbeschikbaarheid geschat werd op basis van de opbrengsten in het controleveldje zonder bemesting, vooral voor N en P. Deze studie bracht hierdoor naar voren dat de relatie tussen N, P en K opname en opbrengst in QUEFTS goed werden beschreven maar dat de onzekerheid in de relatie tussen bodemparameters en nutriëntenopname leidde tot een matige relatie tussen voorspelde en waargenomen opbrengsten. Dit bracht zowel de kracht als de beperkingen in opbrengstvoorspellingen van het huidige QUEFTS aan het licht onder variabele bodemvruchtbaarheidscondities die zo typisch zijn voor landbouw ten zuiden van de Sahara. Actuele opbrengsten voor velden zonder of met minimale bemesting gaven een goede benadering van de beschikbaarheid van nutriënten als aangenomen wordt dat de groei van het gewas beperkt wordt door nutriëntenbeschikbaarheid en de concentratie van nutriënten onder beperkte condities redelijk constant zijn. Dit geeft een kosteneffectieve en redelijk robuuste mogelijkheid om de opbrengstrespons op meststofgiften op bedrijfsniveau te verbeteren.

Hoofstuk 5 was gericht op het verkrijgen van inzicht in de opbrengstrespons op meststoffen op sterk uitgemijnde gronden. In deze studie is gekeken naar de effecten van een gebalanceerde NPK en NP, NK, en PK behandeling op de veldjes in Siaya waar eerder omissie- en controle behandelingen hadden gelegen. In deze studie is ook het RC-P model onder de loep genomen om het verloop en herstel van de P toestand van de bodem te beschrijven en kwantificeren. Percelen met een zeer lage bodemvruchtbaarheid hadden een sterke opbrengstrespons op gebalanceerde NPK giften. In het tweede seizoen met NPK giften na de omissieproef waren de maisopbrengsten (bij een droge stofgehalte van 88%) respectievelijk 5,5 t/ha voor de controle, 6,7 t/ha voor PK, 6,5 t/ha voor NK en 7,0 t/ha voor NP behandeling, ten opzichte van 7.5 t/ha voor de doorlopende behandeling met alleen een NPK gift. De uitkomsten laten zien dat de opbrengstrespons op sterk uitgemijnde maar klei-rijke gronden in West-Kenia na NPK bemesting sterk is en hoge opbrengsten mogelijk zijn zonder voorafgaande investeringen om de organische stof- en bemestingstoestand van de bodem te herstellen. Het aanbrengen van geplaatste P bemesting naast de zaden gaf een sterk verbeterde P terugwinning van de gegeven P bemesting door het gewas. Het RC-P model liet een verbeterde voorspelling zien van de P terugwinning als rekening wordt gehouden met plaatsing van P meststoffen op deze uitgemijnde gronden. Omdat alle velden sterk reageren op NPK bemesting is het niet nodig om te focussen op de verbeteringen van bodemvruchtbaarheid. In conclusie is voor de uitgemijnde gronden van Siaya een focus op de bemesting van de plant nodig voor intensivering van gewasproductiviteit waarbij de bodemvruchtbaarheid in de loop van de tijd zal verbeteren zonder extra investeringen van de boer.

In hoofdstuk 6 worden de bevindingen van de hoofdstukken 2 tot en met 5 geïntegreerd om inzicht te verschaffen voor de duurzame intensivering van de maisproductiviteit met kunstmestbemesting. Om de bodemvruchtbaarheid van sterk uitgemijnde gronden te verbeteren is een regelmatige toediening van minerale bemesting, waarmee de behoefte aan nutriënten voor gewasopname voor een groeiseizoen gedekt wordt, een betere strategie dan een eenmalige grote dosis. Een evaluatie van opties voor intensivering op sterk verarmde bodems bracht aan het licht dat regelmatige bemesting gericht op de nutriëntopname van de plant, en niet de bodem, een duurzame strategie is om maisopbrengsten te verhogen. Ook zijn opties voor een geïntegreerd management van bodemvruchtbaarheid verkend. Er kwam naar voren dat de efficiëntie van kunstmest kan worden verbeterd door rekening te houden met ruimtelijk patronen van opbrengst en gebruik van dierlijke mest op een bedrijf. Als conclusie kwam naar voren dat een aanpassing van P en K bemestingen op basis van dierlijke mestgebruik in het verleden en gezamenlijke toediening van N met hoogwaardige organische bronnen nodig is om de gebruiksefficiëntie op veldniveau te verbeteren.

Dit proefschrift geeft een verbeterd begrip van de oorzaken van variatie en ruimtelijke verdeling van opbrengsten en bemestingsresponsen en de veranderingen in een serie van seizoenen op kleine landbouwbedrijven te zuiden van de Sahara, onder invloed van gebalanceerde en ongebalanceerde bemestingen. De resultaten uit dit proefschrift geven handvatten voor een verbeterde en meer doelgerichte kunstmestbemesting wat zal leiden tot verbeterde voorspelbaarheid van opbrengsten en opbrengstresponsen op gegeven kunstmestgiften. Resultaten in dit proefschrift laten ook zien dat met een gebalanceerde NPK bemesting en goed management een maïsopbrengst van 4.5 t/ha, welke nodig is voor volledige zelfvoorziening van mais in de oost-Afrika regio, goed haalbaar is ondanks de grote heterogeniteit in bodemgesteldheid.

The completion of this PhD thesis would not have been possible without dedicated support from many people and institutions. First of all, I would like to pass my heartfelt gratitude to Shamie Zingore my co-promotor and direct supervisor at IPNI/APNI. You not only crafted an opportunity for me to conduct my PhD within the limited budget of the 4R Nutrient Stewardship project in western Kenya, but also provided a link to Wageningen University where my capacity as a researcher has been greatly enhanced. My gratitude also goes out to Ken Giller my promotor for the opportunity to be part of the PPS group. Your expertise in farming systems of sub-Saharan Africa, and thought-provoking questions and insights helped to solidify, and place in better context a lot of ideas explored in this thesis. I am also very grateful to my second co-promotor and daily supervisor Tom Schut. You without complains suffered the unfortunate burden of often being the first to review initial drafts of this work, most of which are now nowhere close to what is in this thesis! Thanks for always making time for our weekly skype meetings during my time away from Wageningen. These meetings were the source of many light bulb moments without which, this thesis would not be a reality.

At PPS, I was fortunate to be part of the ‘batch of 2014 PhDs’ including Jannike, Ilse, Comfort, Ashenafi, Daniel and others. Walking this path together by relating to low moments suffered, and sharing in high moments experienced, has helped to smoothen what is in reality an arduous journey. To those still walking the journey, hang in there, the end is near! In my time at PPS, I was also fortunate to share offices, lunches, coffees, discussions and other moments with many people. Thank you: Esther R, Renske, Eva H, Eva T, Esther N, Lotte K, Wytze, Marius, Edourd, Alain, Lotte W, Hanna, Paul, Na, Wilson, Keiji, Hannington, Marcel, Marloes, Martin, Maja, Katrien, Marieke, Joost, Gerrie, Pytrik, William and many others. Thank you also to Ria, Linda, Karen, Charlotte and Alex-Jan, for your administrative and logistical support especially during my time away from Wageningen.

Away from my office life, my stays in Wageningen and the Netherlands in general were made pleasant and bearable through the support of several people. I am indebted to the Hoogmoed family: Willem, Annelies, Marianne and John for taking time to show me what else the Netherlands has to offer, and most notably for the airport pick up during my very first visit to the Netherlands. To Anthony Njenga and Marieke Faas, thanks for opening up your home to me. Time spent with you and your girls Sayari and Amana was a welcome distraction whenever I didn’t want to think about my PhD. To Edu, Lincoln, Mike and other Kenyans living in the Netherlands, moments shared helped to ease the burden of being away from home for extended periods. My appreciation also goes out to the 'Kenyans in Wageningen' students' group. You served as a 'one stop shop' for matters related to settling down in Wageningen, and as the first point of call when in need of something from Kenya or vice versa. A special mention to Faith, for helping me find my way back to my room during my very first day at the university, when I had no clue how to get back to Haarweg! To the 'gym team': Victor, Patrick, Elke, Kate, Stefano, Sergio, Sotiris, Elena, Pong, Guido, Christian (the Mexican), Peter, Alejandra, Daniel, Matej, and Camiel, the dinners, drinks, and moments shared made Beringhem home away from home. Thank you.

I am grateful to my colleagues both past and present at the IPNI/APNI office in Nairobi including: James, Jairos, Guillaume, Tiemen, Joses, Esther, and Beverly for offering both moral and scientific support. Ann, Angela, Patrick and Jeremiah are equally appreciated for all the logistical support during my PhD. I am especially grateful to Joseph Sewe the IPNI field officer in western Kenya. Your meticulous support and management of all field experiments over the course of my study was the very basis of the chapters in this thesis. I wish you and your lovely family the very best in life. To colleagues at IFDC with whom I have shared offices in the Nairobi office, thanks for always checking on me and my progress, even though I rarely had a solid answer to the question 'when are you finishing?'!

I will be eternally grateful to farmers in Sidindi, western Kenya for offering their farms as experimental sites for the entire length of this PhD study. It is my hope that the trainings on '4R Nutrient Stewardship' offered during field days conducted on the side-lines of this PhD will continue helping you to improve the productivity of your farms. To Ambrose, Julius, Samson, and Arthanasio who did not live to see the end of this project, your participation was not in vain.

I am thankful to Prof Daniel Mugendi my Msc supervisor and mentor during my Bsc for sowing in my mind the seed of agricultural research, at a point in my life when all I wanted to do was finish my undergraduate studies and start earning! Interactions with researchers at CIAT during my Msc studies and first work assignment also helped to set me on this PhD journey. I am especially grateful to Job Kihara for offering me an early opportunity to delve in the rigours of scientific publishing.

Finally, I would like to thank my family for the enduring support during this journey. To my mum Teresia, sisters Monica and Judy, and my brother George, thank you for the moral support, and for helping with my young family and other affairs during my time away from Kenya. You are a true representation of what family is all about. To my wife Fridah, you have been my source of strength when the going was proving too tough. Thank you for always offering a listening ear as I vented my frustrations when scripts were not running or when writing was not progressing. Thank you for your understanding during periods when I had to be away from home, or had to work extended hours at the office. Thank you for believing in me and the dreams that I harbour for our family. Thank you for taking care of our girls and for holding everything together in my absence. To my daughters Skeetah and Sierra, watching you grow over the course of my PhD has been a source of great joy. Your innocence and curiosity warmed my heart and gave me the purpose to strive on.

About the author

Samuel Njoroge was born on 25th May 1983, in Ruiru a small industrial town in the current Kiambu county of Kenya. He grew up in the same town and attended his primary and secondary education at Saint Georges Primary School Ruiru, and Thika High School respectively. With an initial interest in environmental matters, he enrolled for a bachelor's degree in Environmental Science at Kenyatta University in 2002. In 2005, an internship at the International Centre for Tropical Agriculture (CIAT) in Nairobi sparked interest in agricultural research following interactions with researchers at CIAT. Following his graduation in 2006, he subsequently enrolled for an Msc in Agroforestry and Rural development at Kenyatta University. For his Msc project, he assessed the role of organic and inorganic resources applications in carbon cycling and soil aggregation through a joint scholarship from Kenyatta University and CIAT Kenya.

Samuel completed his Msc studies in 2010 and joined CIAT Kenya where he worked for three years as a research assistant in the Africa Soil information Systems (AfSIS) project. From early 2013, he joined the International Plant Nutrition Institute (IPNI) sub-Saharan office program in Nairobi, Kenya as a project manager. At IPNI, Samuel is responsible for the implementation of projects on 4R nutrient stewardship in sub-Saharan Africa through collaborations with local and regional research institutes. In September 2014, Samuel was admitted as a PhD student in the Plant Production Systems Group of Wageningen University under a fellowship from IPNI. His PhD focused on achieving an improved understanding of the variability in maize yield response to fertilizer application in western Kenya, and the identification of the key drivers of this variability.

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Peer reviewed scientific publications

Njoroge, S., Schut, A. G. T., Giller, K. E. & Zingore, S. (2017). Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. Field Crops Research 214: 321-330.

Njoroge, S., Schut, A. G. T., Giller, K. E. & Zingore, S. (2019). Learning from the soil's memory: Tailoring of fertilizer application based on past manure applications increases fertilizer use efficiency and crop productivity on Kenyan smallholder farms. European Journal of Agronomy 105: 52-61.

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., **Njoroge, S.**, Palm, C. & Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. Agriculture, Ecosystems & Environment 229: 1-12.

Nziguheba, G., Zingore, S., Kihara, J., Merckx, R., **Njoroge, S.**, Otinga, A., Vandamme, E., & Vanlauwe, B. (2015). Phosphorus in smallholder farming systems of sub-Saharan Africa: implications for agricultural intensification. Nutrient Cycling in Agroecosystems, 1-20.

Kihara, J., Huising, J., Nziguheba, G., Waswa, B. S., **Njoroge, S.**, Kabambe, V., Iwuafor, E., Kibunja, C., Esilaba, A. O. & Coulibaly, A. (2015). Maize response to macronutrients and potential for profitability in sub-Saharan Africa. Nutrient Cycling in Agroecosystems: 171-181.

Kihara, J. & **Njoroge, S**. (2013). Phosphorus agronomic efficiency in maize-based cropping systems: A focus on western Kenya. Field Crops Research 150: 1-8.

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review of literature (4.5 ECTS)

Spatiotemporal dynamics of crop yield responses to fertilizer applications

Writing of project proposal (4.5 ECTS)

Spatiotemporal dynamics of crop yield responses to fertilizer applications

Post-graduate courses (9.1 ECTS)

- Land dynamics: getting to the bottom of Mount Kenya; PE&RC (2015)
- Spatial data analysis and modelling for agricultural development, with R; University of California, Davis (2016)
- Multivariate analysis; PE&RC (2017)
- R and Big data; PE&RC (2017)
- Calibration of nutrient expert for improved fertilizer use recommendations; IPNI, South East Asia program (2018)

Invited review of (unpublished) journal manuscript (2 ECTS)

- Field Crops Research: poor responsive soils in western Kenya lead to nutrient imbalances in maize and preclude fertilizer use due to unacceptable Value Cost Ratio’s (VCR) (2016)
- Georderma: long-term changes of soil chemical characteristics in no-till conservation agriculture in a semi-arid environment of South Africa (2018)

Deficiency, refresh, brush-up courses (15 ECTS)

- Research methods in crop science; WUR (2014)
- Quantitative aspects of production; WUR (2014)
- Systems analysis simulation; WUR (2014)

Competence strengthening / skills courses (2.4 ECTS)

- Writing grant proposals; PE&RC (2018)
- Effective project implementation, planning, execution, and management of research projects; IPNI- Sub-Saharan Africa program (2018)

PE&RC Annual meetings, seminars and the PE&RC weekend (1.8 ECTS)

- PE&RC Introduction weekend (2014)
- PE&RC Last year weekend (2017)

Discussion groups / local seminars / other scientific meetings (4.5 ECTS)

- Weekly lunchtime seminars; PPS & CSA (2014)
- Implementation and out-scaling of balanced crop nutrition in Africa; AGRA & IFDC (2015)
- Optimizing fertilizer recommendations in Africa; OFRA (2015)
- Weekly lunchtime seminars; PPS & CSA (2018)

International symposia, workshops and conferences (4.7 ECTS)

- European Society of Agronomy Congress; Geneva, Switzerland (2018)
- Phosphorus in Soils and Plants (PSP6); Leuven Belgium (2018)

Lecturing / Supervision of practicals / tutorials (1.2 ECTS)

- Crop physiology and Environment (2017)

Supervision of MSc students (3 ECTS)

- Paul Ravensbergen: testing spectraCrop plant vitality and P tester

The research described in this thesis was financially supported by funding from Agrium to the International Plant Nutrition Institute (IPNI), for research on 4R Nutrient Stewardship in western Kenya.

Financial support from Wageningen University for printing of this thesis is gratefully acknowledged.

Cover design by Samuel Njoroge and Conrad Mudibo (www.ecomedia.co.ke)

Printed by ProefschriftMaken, www.proefschriftmaken.nl