A CROSS-COUNTRY ANALYSIS OF FERTILIZER USE PROFITABILITY IN KENYA, ZAMBIA, AND MALAWI

By

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ABSTRACT

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Maize production intensification is becoming increasingly important to food security in Sub-Saharan Africa (SSA). Fertilizer is an essential part of that process but continues to be underutilized by farmers across SSA and many claim is unprofitable. In order to determine how accurate the widely held perception that fertilizer use is not profitable is, and to what extent profitability is present among farmers who use fertilizer, this research analyses fertilizer use profitability trends in Kenya, Zambia, and Malawi. Using household survey data, the research is conducted in a two-step process consisting of maize yield response estimation and value-cost ratio calculations. Results show that while current use is profitable for the majority of farmers in Kenya and Zambia, it is not profitable for the majority of farmers in Malawi. Furthermore, there room for expanded profitable use of fertilizer in Kenya and Zambia, but not in Malawi. Calculations of profitability point to unfavorable price ratios as the main issue hindering profitability in all three countries.

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Chapter 1: Introduction

1.1 Introduction

Despite being the most important food security crop for millions of rural households in Sub-Saharan Africa (SSA), there has been very little progress in maize productivity. Average maize yields and yield growth rates are much lower in Sub-Saharan Africa than in other parts of the world. While the world average maize yield doubled from 2.5 to over 5 tons per hectare between 1960 and 2008, Africa's yields did not change, remaining at less than 2 tons per hectare (Manitra A. Rakotoarisoa, Missimo lafrate, and Marianna Paschali 2011) .

With stagnant productivity against increasing demand with growing populations, Africa changed from being a net exporter of maize to a net importer of maize in the early 1980's (Manitra A. Rakotoarisoa, Missimo lafrate, and Marianna Paschali 2011). However, importing enough food to fill these gaps is not a logistically or financially viable option for SSA given the lack of adequate infrastructure to receive, distribute and store food (ports, roads, storage), lack of foreign reserves, and the weak and volatile local currencies. Unable to meet food requirements of growing populations through domestic production or imports, many countries in SSA are faced with maize deficits and resulting food insecurity.

Looking at Asia's experience in yield growth during the Green Revolution, one of the key elements that is credited with as much as 50% of the region's yield growth during that time that is notably lacking in SSA is fertilizer. According to The World Bank's World Development Indicators, fertilizer consumption rates in SSA are only 18 kg of nutrients per hectare of arable land, compared to 125 in Latin America, 150 - 246 in Asia (South Asia and East Asia, respectively), and 120 world average (The World Bank, World Development Indicators 2013).

Nyoro et al found that bringing fertilizer response rates among the bottom half of the distribution up to the mean would contribute substantially to household and national food security (Nyoro et al., 2004).

In addition to boosting productivity, while organic fertilizer offers minimal nutrients for soil, inorganic fertilizers has been found to restore soil fertility, especially where nutrient depletion is the major soil degradation issue (Wilfred Mwangi 1996). Contrary to the appearance of land-abundance, extreme land scarcity in much of SSA has created challenges of low soil fertility as a result of shortening or elimination of fallow periods (Derek D. Heady, T.S.Jayne 2014; T.S. Jayne, Jordan Chamberlain, Derek D. Headey 2014; Milu Muyanga, T.S. Jayne 2014; Derek Headey, Mekdim Dereje, Alemayehu Seyoum Taffesse 2014). With these land constraints in SSA, productivity needs to grow by increasing output per hectare, highlighting the importance of increasing inorganic fertilizer use in order to attain soil fertility levels required to achieve that outcome (Matlon, P. 1987).

There are both supply and demand constraints that have hindered fertilizer use and market growth in Sub-Saharan Africa (SSA). On the supply side, poor infrastructure and heavy reliance on imports are the main constraints. Nearly all fertilizer in SSA is imported, causing fertilizer prices to be more than double the price farmers pay in Asia and the US (Michael Morris, Valerie A. Kelly, Ron J. Kopicki, and Derek Byerlee 2007). These high prices are driven by high transport and logistics costs that were found to be three to four times higher than they are in the US (Paul W. Heisey, and George W. Norton 2007). On the demand side, many studies cite low maize yield response to fertilizer, and the resulting unprofitability of fertilizer use as the main factors hindering demand for fertilizer in SSA (Melinda Smale, Derek Byerlee, Thom Jayne 2011).

This thesis analyzes profitability of fertilizer use on maize in SSA. More specifically, this analysis evaluates the commonly cited generalization that fertilizer use is not profitable in SSA, and two commonly cited reasons for this trend:

- Weak crop response to fertilizer
- Unfavorable price relationships

This paper assesses these hypotheses in SSA by comparing trends in three different countries: Kenya, Zambia, and Malawi. These three countries are selected for comparison based partially on data availability but also because they offer interesting historical differences in public expenditure patterns to agriculture that may partially explain differences in returns to fertilizer use across the three countries and thereby provide important implications for policy.

I hypothesize that, in general, price ratios will be the limiting factor for profitability and that crop response to fertilizer will be sufficient. More specifically, I hypothesize that crop response will meet adequate agronomic standards in the main maize producing areas of each country (including Rift Valley, Nyanza, and Western Provinces in Kenya; Eastern, Central, and Southern Provinces in Zambia; North and Central regions in Malawi), but may fall short in all other areas. Secondly, I hypothesize that the input to output price ratios will meet adequate economic standards in most areas in Kenya, but not in Zambia and Malawi based on the lower level of infrastructure (which may add to costs of both input and output) and lower level of investment in agriculture in these two countries. Finally, I hypothesize that fertilizer use is generally profitable in all countries, but with little to no room for expanded profitable use in Kenya, and more room for expanded profitable use in Zambia and Malawi.

In my analysis I find mixed results for my hypotheses. My results confirm my hypothesis that maize response to fertilizer is quite high in all three countries, with both marginal and average physical products of nitrogen both generally well above defined thresholds. Input to output price ratios provide evidence that price ratios are too high according to economic standards in Zambia and Malawi, as expected, and also in Kenya, which was an unexpected but important result, highlighting the continued high prices farmers face there despite the liberalization and commonly held perception of resulting declining and favorable prices. Finally, my estimates of profitability of fertilizer use on maize indicate that, while fertilizer use if profitable for the majority of farmers in Kenya and Zambia, profitability rates are very low in Malawi. Furthermore, room for expanded use of fertilizer is lower than expected, while that in Kenya is much higher than expected.

1.2 Motivation and Objectives

Facing land constraints with growing populations, low yields compared to other regions of the world, insufficient maize production to meet requirements and insufficient financial and infrastructure capacity to import maize to fill the supply gaps, intensification of maize production is a widely encouraged approach to meet domestic food requirements in SSA. Fertilizer is a key component of that strategy, but fertilizer demand and use remains very low in most countries of SSA. Consequentially, there is a need for research in order to provide an understanding of the challenges to increasing fertilizer use in SSA and how to best address them.

There are two factors farmers consider in their decision to purchase fertilizer that reflect the main drivers of the weak effective demand for fertilizer: 1. will fertilizer use be profitable, and 2. can the desired amount be acquired. The first question addressing profitability reflects the incentive for a farmer to use fertilizer given input and output prices and the expected crop response to fertilizer application obtained by the farmer. The second question reflects the capacity of a farmer to obtain fertilizer (Valerie Kelly 2006).

This thesis aims to analyze the incentives piece of this puzzle. Although there have been several studies on fertilizer use and, to a less extent, profitability of fertilizer use in SSA, nearly all research has been conducted for a single country. There exist very few studies that consider a wider scope, comparing the drivers and dynamics across countries and attempting to identify the reasons why response rates may vary by region and country.

The main objective of this thesis is to provide estimates of fertilizer use and profitability for maize production by rural households in 22 districts from Kenya, 70 from Zambia, and 26 from Malawi. The analysis also looks at variations in these estimates over time, with four waves of panel data for Kenya covering a ten year time span, two waves of data for Zambia covering a four year time span, and four waves of data for Malawi covering a six year time span. The main questions I ask are:

- How much fertilizer are farmers using on maize fields in Kenya, Malawi, and Zambia?
    - Are fertilizer use rates similar across these three countries?
    - How do fertilizer use rates differ across space and time within each of the three countries?
- What are the maize response rates to fertilizer in Kenya, Malawi, and Zambia?
    - What are the impacts of specific field level characteristics and management practices, household level characteristics, and agro-ecological factors on maize yield?
    - How does the response of maize yield to fertilizer application vary between and within the countries of Kenya, Malawi, and Zambia?
    - Do certain inputs have the same effect on maize yield in different countries?

    - Is the phosphorus to nitrogen ratio of fertilizer applied an important factor in maize response? Are there similarities between maize response rates in regions with similar phosphorus to nitrogen ratio application in different countries?
- Is it profitable for farmers in Kenya, Malawi, and Zambia to use fertilizer?
    - Could households in Kenya, Malawi, and Zambia expand fertilizer use on maize fields?

These questions are answered through specification and estimation of a maize production model and calculation of the value cost ratio of fertilizer use. Using a nationally representative household panel dataset from each country, I conduct a cross-country analysis to estimate maize response rates to fertilizer and fertilizer profitability in Kenya, Malawi, and Zambia.

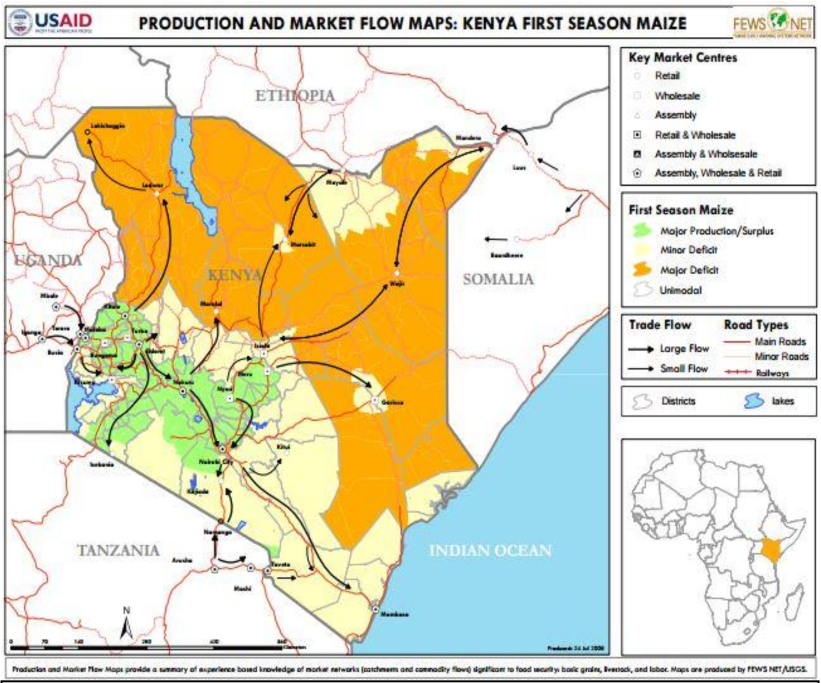
The rest of this paper is organized as follows: Chapter 2 describes maize trends and fertilizer use generally in Kenya, Zambia, and Malawi. I present my conceptual framework and empirical methods in Chapter 3. Chapter 4 describes my data and sample selection method. In Chapter 5, I present the production function estimates, followed by the marginal (and average) products and marginal (and average) value cost ratios for profitability measures in Chapter 6. Finally, I summarize and conclude the findings of the study in Chapter 7.

Chapter 2: Background and Existing Literature

2.1 Maize production, fertilizer use, fertilizer profitability in Kenya, Zambia, and Malawi

2.1.1 Kenya

Figure 1. Kenya Maize Production and Trade Flow Map



Source: FEWS NET fews.net

Maize plays an important role in the everyday diet and food security in Kenya. Kenya is ranked 10th in the world for maize consumption at an average of 171 g/capita/day (based on FAOSTAT data, 2007 – 2009, estimated at 80% extraction from 3 year average) (Peter Ranum, Juan Pablo Pena-Rosas, Maria Nieves Garcia-Casal 204AD). Maize is also one of the most produced crops in the country. Smale and Jayne report average annual production from 1965 to 1980 at 1,757,971 MT, and 2,341,964 MT from 1990 to 2000 (Melinda Smale and T.S. Jayne 2004). Production growth increased from 1965 to 1980 at a rate of 3.3 but declined at a rate of -

1.45 from 1990 to 2000. Smale and Jayne report average yield at 1.31 MT/ha from 1965 to 1980, and 1.65 MT/ha from 1990 to 2000. As shown in Figure 1, the major maize producing areas (marked in green) are the Rift Valley, Western, Nyanza, and parts of Eastern provinces.

Kenya has been deemed as a success story in SSA for maize and input markets. Liberalization of input and maize markets in the 1990's led to declining maize marketing margins as distance to point of sale reduced. Smallholder farms account for 96 percent of all farm households in Kenya and are typically buyers of maize (Melinda Smale, Derek Byerlee, Thom Jayne 2011). However, the maize market continues to be highly concentrated with two percent of farms in survey data accounting for 50 percent of total marketed maize surplus from the smallholder sector (Melinda Smale, Derek Byerlee, Thom Jayne 2011). Food prices have remained very high in Kenya as a result of price supports offered by the National Cereals and Produce Board of Kenya (NCPB) that are above market levels, benefiting maize sellers but increasing costs for maize buyers, the majority of whom are poor smallholders. Despite being high, maize prices in Kenya have been stable as a result of actions of the NCPB and the removal of regional trade barriers in 2005 (Jayne, T.S., R.J. Myers, J.Nyoro 2008; Antony Chapoto and T.S. Jayne 2007).

In Kenya, following the removal of fertilizer price and import controls in the 1990's and liberalization of fertilizer markets, fertilizer consumption doubled by 2007 and smallholder fertilizer use per hectare of maize cultivated increased by 34 percent (Melinda Smale, Derek Byerlee, Thom Jayne 2011). Ariga et al found that percent of households using fertilizer on maize grew from 56 percent in 1996 to 70 percent in 2007 (Isaac Minde, T.S. Jayne, Eric Crawford, Joshua Ariga, and Jones Govereh 2008). However, Jayne et al find that the increase in fertilizer use has not been consistent across the country and is much higher in areas with relatively high and stable rainfall than in the drier areas of the country

As a result of liberalization of the fertilizer market, distance to the nearest fertilizer retailer declined, inflation-adjusted fertilizer marketing margins decreased, causing marketing costs and transaction costs to decline and nitrogen-to-maize price ratios became more favorable (Melinda Smale, Derek Byerlee, Thom Jayne 2011). Minde et al also highlight the Farm Input Promotions (FIPS) program, the CNFA agro-dealer training and credit program, and the Kenya Market Development Programme that increased facilitation and access to extension and credit services by farmers, as drivers of the increased fertilizer use nationwide.

Aside from the economic factors effecting maize production and fertilizer use, Kenya's geography and agro-climatic characteristics are also key elements. Kenya has a wide range of climates and topography, causing rainfall and soil types to vary across the country. There are various classifications of the agro-climatic and agro-ecological zones, but here I use the 7 agro-climatic zones based on annual rainfall as shown in Table 1 below (Sombroek, W.C., Braun, H.M.H., and van der Pour, B.J.A. 1982; Apollo Bwonya Orodho 2006).

Table 1. Agro-Climatic Zones of Kenya

Agro-Climatic Zone	**Classification**	**Annual Rainfall (mm)**	**Cropping Potential**	**Land Area (%)**	**Soil types and characteristics**
I	Humid	1100-27000	High	12	Loamy, sandy clay, alluvial (silts)
2	Sub-humid	1000-1600	High		Red clay, loamy sandy soils, sandy loam
3	Semi-humid	800-1400	High		
4	Semi-humid to semi-arid	600-1100	Medium	5	
5	Semi-arid	450-900	Low	15	Shallow, lava soils
6	Arid	300-550	Low	22	
7	Very Arid	150-350	Low	46	

Modified from Orodho (2006), and Sombroek et al (1982)

In much of Kenya the soils are considered to be deficient in nitrogen and phosphorus, with the drier areas especially low in organic matter due to low rainfall. As shown in Table 1, soils vary considerably even within the climatic zones.

Research by Meghan Sheahan analyzes the profitability of fertilizer use on maize in Kenya (Sheahan, M., Black, R., & Jayne, T. S. 2013). They find that fertilizer is being used at or beyond the most profitable levels in the highest potential areas, slightly below maximum profit levels in the marginal lowlands, below profitable levels in the lowlands, and should be reduced in other parts of the country. Duflo et al (Esther Duflo, Michael Kremer, and Jonathan Robinson 2008) find that the quantity of fertilizer recommended by the Kenyan Ministry of Agriculture (100 kg per acre of maize, using Di-Ammonium Phosphate (DAP) fertilizer at planting, and Calcium Ammonium Nitrate (CAN) fertilizer at top dressing, approximately one to two months after planting) is not profitable, but that when using appropriate quantities, fertilizer use was indeed profitable in Kenya. Smale et al state that there is still potential for efficiency gains through soil and moisture management improvement to increase maize yield response to fertilizer (demand side), and infrastructure improvement (ports, roads) to reduce transport costs on the supply side (Melinda Smale, Derek Byerlee, Thom Jayne 2011). Finally, Ariga and Jayne (Joshua Ariga and T.S.Jayne 2009) find a rising proportion of farmers using fertilizer over time, and that VCR estimates are above 2 for most of the country, including most of the agro-ecological zones.

2.1.2. Zambia

Located on the great plateau of Central Africa, most of Zambia is composed of highland plateau. There are three main broad agro-ecological zones in Zambia, as presented in Table 2 below. Soil types and characteristics vary across and within the zones. Region II is often broken up into IIa and IIb, with the more productive soil types (Haplic Lixisols Haplic Luvisols, and Haplic Acrisols) in region IIa (Central area), and the infertile, coarse sands (Ferrallic Arenosols) in the IIb region (Western plateau) (Eroarome Martin Aregheore 2009).

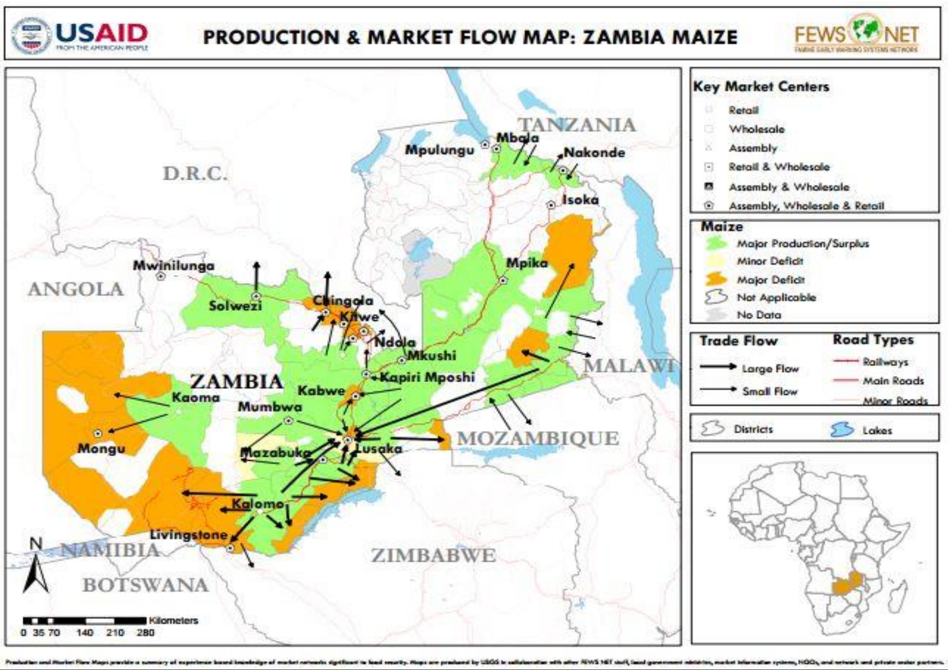
Table 2. Zambia's Agro-ecological zones

Zone	**Location**	**Annual Rainfall (mm)**	**Soil Types**
Region I	South	< 800 per short season	Haplic Luvisols, Haplic Solonetz, Dystric Leptosols
Region II	Central	800-1000	Haplic Lixisols, Haplic Luvisols, Haplic Acrisols, Ferrallic Arenosols
Region III	North	>1000	Haplic Acrisols

Maize accounts for more than 50 percent of total calories in the daily diet in Zambia (Melinda Smale, Derek Byerlee, Thom Jayne 2011). Ranked 4th in the world for maize consumption, the estimated average national consumption is 243 g/capita/day (based on FAOSTAT data, 2007 – 2009, estimated at 80% extraction from 3 year average) (Peter Ranum, Juan Pablo Pena-Rosas, Maria Nieves Garcia-Casal 204AD).

The major maize producing areas of the country, shown in green on Figure 2, include Eastern, Central, and Southern provinces, with Western province making up the bulk of the country's maize deficit area (shown in orange). The Zambian Government began policies in 2002, including the Fertilizer Support Programme (FSP), under its Poverty Reduction Strategy (PRSP) in order to boost national maize production. However, despite these efforts, fertilizer consumption has only slightly increased since then, and maize yields are still low. Average national yield is cited as 1.6 MT/ha from 1970 to 2000, with a positive growth rate in yield from 1970 to 1989 (4.9 percent) but a negative growth rate from 1990 to 2000 (-.8 percent) (Melinda Smale and T.S. Jayne 2004). Xu et al report maize yields between .7 and 2.5 tons per hectare for 75 percent of households (Z. Xu, Z. Guan, T.S. Jayne, and Roy Black 2009).

Figure 2. Zambia Maize Production and Trade Flow Map



Source: FEWS NET fews.net

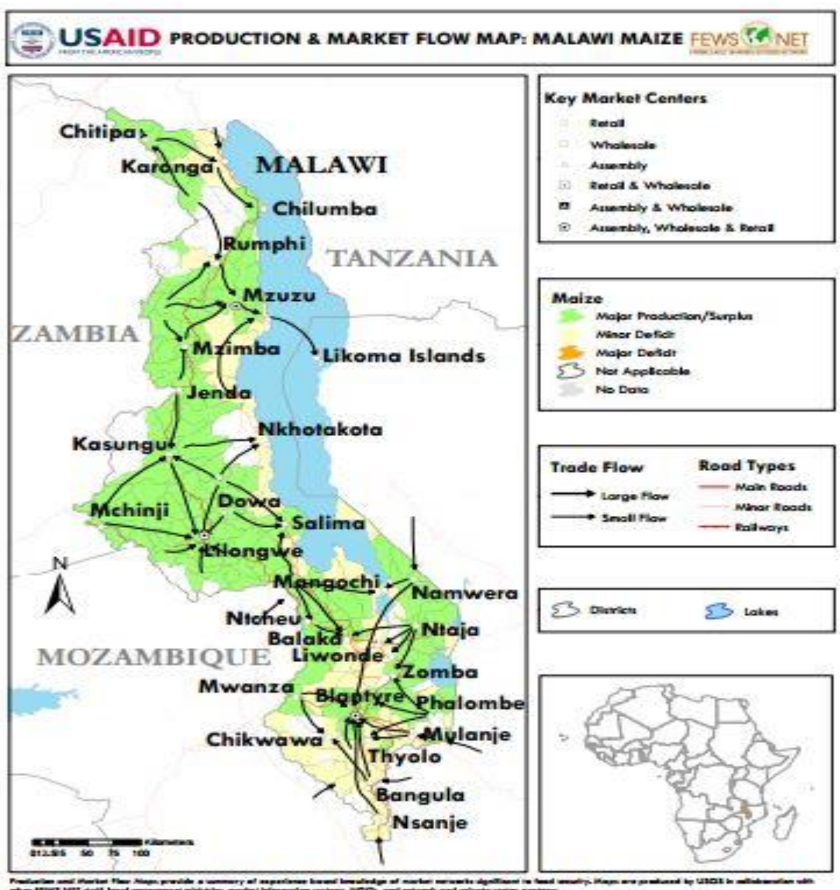
General price inflation and currency depreciation against the USD has led to falling maize prices in Zambia. However, nitrogen/maize price ratios have stayed nearly unchanged in Zambia from 1996 through 2008 (Isaac Minde, T.S. Jayne, Eric Crawford, Joshua Ariga, and Jones Govereh 2008).

Like Kenya, profitability of fertilizer use in Zambia has also been well researched. Xu et al found that there was a wide range in nitrogen-maize price ratios in Zambia, reaching levels that were 20 percent higher in remote areas than other parts of the country. As a result, fertilizer was only profitable for a small portion of farmers (Z. Xu, Z. Guan, T.S. Jayne, and Roy Black 2009). A study by MACO/CSO/FSRP (2008) based on CSO survey data for 2007/08 indicates that mean maize yield increases per ton of fertilizer applied are lowest for the largest farm size category (3.32 metric tons/hectare for farms between 5-20 hectares), the highest for farmers in the 1.7-5.0 hectare category, and the smallest farms (less than one hectare) fell in the middle (4.55 mt/ha) (Isaac Minde, T.S. Jayne, Eric Crawford, Joshua Ariga, and Jones Govereh 2008).

2.1.3 Malawi

Maize is by far the dominant staple food in all parts of Malawi. Like Zambia, maize accounts for more than half (54%) of total calories (Melinda Smale, Derek Byerlee, Thom Jayne 2011; Nicholas Minot 2010). Malawi is ranked 2nd highest in the world for maize consumption with an average consumption of 293 g/capita/day (based on FAOSTAT data, 2007 – 2009, estimated at 80% extraction from 3 year average) (Peter Ranum, Juan Pablo Pena-Rosas, Maria Nieves Garcia-Casal 204AD).

Figure 3. Malawi Maize Production and Trade Flow Map



Source: FEWS NET fews.net

Average national production is estimated as 1,379,580 MT from 1983 to 1993, and rose up to 1,753,398 MT from 1994 to 2000. However, there is also a high level of production fluctuation from year to year (The Maize in Zambia and Malawi 2008). According to Smale et al, Malawi is expected to be one of the best suited areas to success in maize production intensification but yield growth remains low (Melinda Smale, Derek Byerlee, Thom Jayne 2011). Average national maize yield in Malawi rose slightly from an average of 1.1 MT/ha between 1983 and 1993, to 1.35 MT/ha between 1994 to 2000 (Melinda Smale and T.S. Jayne 2004). These yield rates remain well below the world average maize yield of 4.2 tons/hectare (The Maize in Zambia and Malawi 2008). As a result, the country frequently faces maize deficits frequently. Figure 3 shows maize production throughout the country however it is important to note that the North and Central regions consistently have better harvests while the South region typically have more variable climate effects that often hamper harvests.

In comparison with Kenya and Zambia, fertilizer use is much lower in Malawi. Heisey and Mwangi estimate that between 1989 and 1993, average fertilizer use (kg/ha) on cropped land was 28.6 in Malawi, compared to 34.5 in Kenya and 60.3 in Zambia (Heisey, P.W. and W. Mwangi 1996). Minde et al found that poorer households were less likely to purchase commercial fertilizer, but there is a lack of research evaluating why (Isaac Minde, T.S. Jayne, Eric Crawford, Joshua Ariga, and Jones Govereh 2008). In their review of maize in Malawi, the Japan Association for International Collaboration of Agriculture and Forestry (JAICAF) states that many farmers do not apply fertilizer due to lack of financial capacity to do purchase it, causing a lack of soil fertility replenishment (The Maize in Zambia and Malawi 2008).

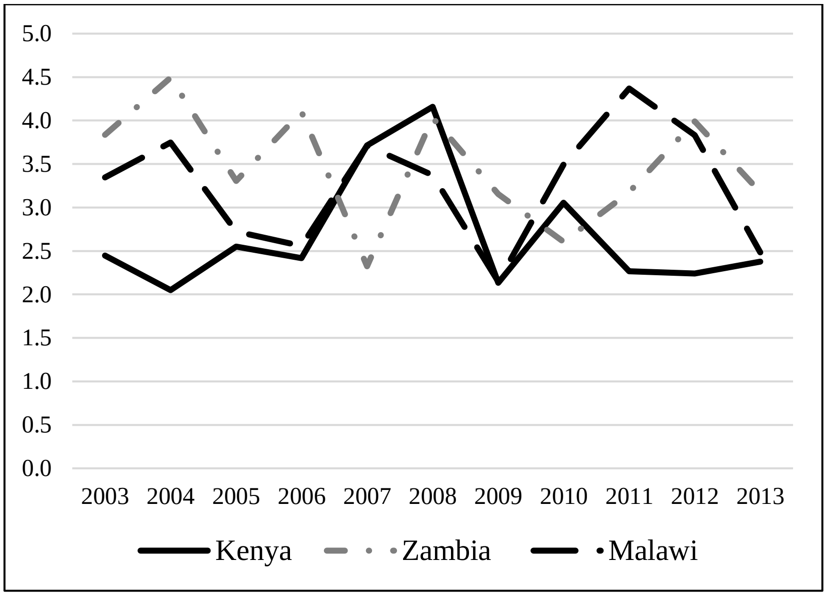
Several studies find fertilizer use profitability to be limited or negative for many farmers in Malawi (Wiyo, K. and J. Feyen. 1999; Ricker-Gilbert, J., Jayne, T.S., Chirwa, E. n.d.; Kamanga, B.C.G, S.R. Waddington, A.M. Whitbread, C.J.M Almekinders, and K.E. Giller. 2014). Both agronomic and economic factors seem to play a role.

Table 3. Agro-ecological Zones in Malawi	
Zone	**Soil types and characteristics**
Highlands	Latosols
Escarpments	Thin Latosols
Plateaux	Well-drained latosols, poorly-drained sand and clay
Lakeshore and Upper Shire Valley	Mopanosols
Lower Shire Valley	Hydromorphic, alluvial, colluvial, saline

On the agronomic side, the five main landform areas make up the main agro-ecological zones in Malawi (Len Reynolds 2000), as shown in Table 3. Annual rainfall ranges from 800 to 1400 mm in most areas. Soil acidity in Malawi is an issue in the high rainfall and high altitude areas (Kabambe, V.H., A. D. C. Chilimba, A. Ngwira, M. Mbawe, G. Kambauwa and P. Mapfumo. 2012).

On the economic side, although there is a high level of price instability for maize in all of Africa, Smale et al report that Malawi has the greatest level of price volatility of maize markets in southern Africa (Melinda Smale, Derek Byerlee, Thom Jayne 2011). Maize prices are largely determined by domestic supplies and demand with imports and exports making up an insignificant percent of domestic consumption (3%) and production (6%), respectively (Nicholas Minot 2010), highlighting the largely non-traded nature of domestic maize over the sample period.

Figure 4. Input/Output Price Ratios 2003-2013



Source: Kenya Ministry of Agriculture, Zambia Ministry of Agriculture and CSO, Fertilizer Association of Malawi, FEWS NET fews.net

Comparing the fertilizer to maize price ratio trends over time in Kenya, Zambia, and Malawi, the price ratio has generally been the lowest and most stable in Kenya (Figure 4). In contrast, price ratios have consistently been quite volatile in both Malawi and Zambia.

Chapter 3: Conceptual Framework and Methodology

This research is done in two stages. The first stage determines the relationship between maize yield and fertilizer (nitrogen) application rates, soil characteristics, rainfall, hybrid seed use, field size, and household assets in Kenya, Malawi, and Zambia by estimating cross-country maize production function. In the second stage, based on results from the CRE model, I use the marginal and average products of nitrogen, and prices of maize and fertilizer, to then calculate the profitability of fertilizer application on maize fields in each of the three countries. This chapter will discuss the methodology of both stages. Following the sequence of analysis used by Sheahan et al (Sheahan, M., Black, R., & Jayne, T. S. 2013) in their analysis of fertilizer profitability in Kenya, which is based on the analyses done by Hassan (Hassan, R. M., Murithi, F., & Kamau, G. 1998), I augment the scope of the analysis by covering a cross-country data set.

3.1 Production Function and Estimation technique

In the first stage of my analysis, I estimate a maize yield response model expressed as:

$$\mathbf{Y}\boldsymbol{ijt} = (\boldsymbol{Xkijt}, \boldsymbol{Zkijt}, uijt)$$

$\mathbf{Y}\boldsymbol{ijt}$ refers to the maize yield per hectare (in kilograms) of a plot i for household j in year t which is a function of vectors $\boldsymbol{Xkijt}$ and $\boldsymbol{Zkijt}$. $\boldsymbol{Xkijt}$ is a vector of physical inputs applied by the household to a plot (such as fertilizer) and agrological conditions (for example, rainfall). $\boldsymbol{Zkijt}$ is a vector of household characteristics that are also likely to affect crop yield (such as household capital). $\boldsymbol{uijt}$ is the error term containing unobserved characteristics of the production system that affect crop yield. Analysis is conducted at the plot level and I assume that households optimize at the plot level.

While there are several different functional forms of production functions, there are three main functional forms that stand out in literature; the quadratic, von Liebig, and the linear response and plateau (LRP) function forms. Although Ackello-Ogutu et al. (Ackello-Ogutu, C., Paris, Q., & Williams, W. A. 1985) and Grimm et al. (Grimm, S. S., Paris, Q., & Williams, W. A. 1987) found that the von Liebig and LRP models produce consistent results, these models assume that yield will be constrained by the most limiting input and allow only one input to be the same limiting input across all cases. This assumption would not hold or fit the cross country cases used for this analysis that includes a great deal of heterogeneity across fields. Quadratic functional form is commonly used in crop yield response analysis because it imposes concavity and diminishing return effects. A quadratic functional form is also advantageous given the tendency towards nonlinear trends that results from aggregation across space, especially when there is a high degree of heterogeneity across plots. Using data across space from three very different countries, there is a high degree of heterogeneity across my sample making the quadratic form a good fit. Finally, although I do not include zero values in my dependent variable, there are zero values in the independent variables (including fertilizer use), which the quadratic form allows for, further making it an appropriate form for my analysis.

I therefore estimate a quadratic production function that is based on the following form:

$$Y_{ijt} = \sum (x_{kijt} + x_{kjijt}^2) + \sum (z_{kijt} + z_{kjijt}^2) + \sum x_{kijt} z_{kijt}$$

I modify this quadratic form to include only the interactions that fit with the available variables and are supported by conceptual theory. Plots from all three countries are pooled and estimated in one model. Since we could not match plots from different time periods, we estimate at the plot level but with household level fixed effects to account for unobserved household characteristics correlated with input use and yield.

Since I am using a panel dataset, random effects (RE), fixed effects (FE), and correlated random effects (CRE) are all potential estimation techniques. Two characteristics of my data need to be considered when choosing the most appropriate estimation technique: correlation between unobserved effects and observed independent variables, and time constant parameters. In the data set used for this analysis, it is possible that there are unobserved household effects, such as household farm managerial skill, present that are expected to be correlated with other key explanatory variables. For example, farm management skill is expected to be correlated with fertilizer use. This correlation between the unobserved effect in the error term and independent variables would cause ordinary least square (OLS) estimators to be biased. Random effects estimator assumes that unobserved heterogeneity is uncorrelated with the independent variables so this assumption will also not hold. The fixed effects estimator does control for correlation between unobserved effects and independent variable, but it does not allow for estimation of time invariant parameters, which are included in this analysis (such as soil quality). The correlated random effects estimator, however, controls for correlation between unobserved heterogeneity and independent variables, and also estimates effects of time invariant variables. CRE also has the benefit of estimating unbalanced panel datasets which is essential for this analysis since we are not able to match plots across years but can identify households across years (Jeffrey M. Wooldridge 2010).

CRE models use the Mundlak-Chamberlain (MC) device to control for unobserved heterogeneity (such as farmer skill) and its correlation with other observable independent variables. The MC device allows for correlation between the omitted variable (unobserved heterogeneity) c_j and explanatory variables x_k such that:

$$c_j = \tau + \bar{x}_k\gamma + a_{ijt}$$

where $\bar{x}_k$ is a vector of average values of each time-variant input x_k at the household level j across all waves of the panel, c_j is constant, γ is a parameter vector, and a is i.i.d, normally distributed and independent of u_{it} in my response model (Z. Xu et al. 2009). With a linear model, the production function with the Mundlak-Chamberlain device is the same as the household fixed effects estimator.

This analysis will therefore use CRE estimation. I estimate the production function using OLS, and FE as well for comparison (Table A2), but I use the CRE estimation results to analyze the contribution of each input to maize yield and as part of the next stage of fertilizer profitability analysis.

3.2 Calculation of Profitability

In the second stage of my analysis, I use results from the CRE regression of the maize yield response function from the previous chapter to estimate profitability of fertilizer use. In order to do this, I first estimate the marginal physical product (MPP) and average physical product (APP) of nitrogen from the regression estimates and use those values, along with price data, to calculate the marginal and average value cost ratios (MVCR and AVCR) to indicate profitability of fertilizer use.

The marginal physical product (MPP) of an input is a measure of how much more output can be produced by using one additional unit of the given input, all else held constant. The MPP is calculated by taking the first derivative of the production function (Y_{ijt}) with respect to the input (X_{ijt}):

$$MPP_{xijt} = \frac{\partial Y_{ijt}}{\partial X_{ijt}}$$

The average physical product (APP), on the other hand, reflects the average gain in output (maize yield) per unit of input (nitrogen) and is calculated as the change in maize yield (Y) due to the use of fertilizer (X), divided by the quantity of fertilizer used:

$$APP_{xijt} = \frac{Y1_{ijt} - Y2_{ijt}}{X_{ijt}}$$

Furthermore, among the selected sample maize fields, there are fields that produce no, or insignificant amounts of, maize. Drought or other external factors can hinder harvests of all or a portion of a farmers' crops. Excluding fields that have "crop failure," as defined in chapter 5, from the estimation of the marginal and average products (MPP and APP) of nitrogen would lead to an overestimation of the MPP and APP. In order to take into account fields defined as "crop failure" fields in the MPP and APP of nitrogen, I calculate weighted averages of MPP and APP.

The MPP and APP are then used as part of the calculation of the value cost ratios (VCRs), a commonly used measure of profitability of an input. An average value cost ratio (AVCR) is the most commonly used approach for assessing the profitability and therefore the financial incentives for using fertilizer on maize (Valerie Kelly 2006). For my analysis focusing on the profitability of fertilizer use (nitrogen) on maize yield as the output, these components are specifically the marginal or average physical product (MPP or APP) of nitrogen, the input price of nitrogen, and the output price of maize. These relationships are represented in the following equations:

$$MVCR_{nijt} = p_{dt} * \frac{MPP_{nijt}}{w_{dt}}$$

$$AVCR_{nijt} = p_{dt} * \frac{APP_{nijt}}{w_{dt}}$$

Where p_{dt} is the output price of maize of district d in a given year t, w_{dt} is the input price of nitrogen (fertilizer) of district d in a given year t, MPP_{fijt} is the MPP of nitrogen from fertilizer (as calculated above) for plot i for household j in year t, and APP_{fijt} is the APP of nitrogen from fertilizer (as calculated above) for plot i for household j in year t.

The marginal value cost ratio (MVCR) and the average value cost ratio (AVCR) reflect different parts of the profitability analysis. The MVCR measures the gain in income from the last unit of fertilizer, reflecting profitability of a given level of input use and further expanded use. The AVCR measures the total average gain in household income from using a given quantity of fertilizer and therefore indicate overall profitability.

It is widely held in literature that a MVCR or AVCR value of equal to or greater than one indicates fertilizer use levels are profitable for a risk neutral household and there is enough incentive for that household to use or adopt fertilizer. Furthermore, several studies support that a MVCR or AVCR value of 2 indicates profitability of input use level for a risk averse household, and, again, that there is enough incentive for that household to use fertilizer at the price of fertilizer paid by the household and price of sold maize received by the household. However, there three important nuances to note for this analysis. First, these threshold values are based on output prices for net sellers, but only a small percentage of households in SSA are net sellers of maize. Second, following the condition for profit maximization, farmers use an input at the point where the marginal value product is equal to the marginal value cost, or put another way, where the MVCR is equal to one. However, taking into account the risk that farmers face, especially in the SSA context, a MVCR value of above one would be required for farmers to use an input, in this case fertilizer. Third, in line with economic theory, the AVCR should be greater than the MVCR. Therefore, while the AVCR threshold for profitability may be a value of 2, as suggested in other research, the MVCR threshold could be slightly lower and only needs to be above 1. For these reasons, I report AVCR and MVCR values above 1 and 2 to provide a comprehensive overview of how the values measure up to the different thresholds supported in research and economic theory.

Chapter 4: Data and Sample Selection

4.1 Data

To conduct this analysis we use national household survey panel data from each of the respective countries, and geographic information system (GIS) based climate data drawn from the Food and Agriculture Organization of the United Nations (FAO) and the University of East Anglia.

4.1.1 KENYA

For the Kenya analysis, we use data from Egerton University's nationwide Tegemo Rural Household Survey. The survey was part of the Tegemo Agricultural Monitoring and Policy Analysis Project (TAMPA) with support from Michigan State University. Sample households were identified using standard proportional sampling of census data in rural divisions. Households were asked questions pertaining to their agricultural activities, non-agricultural sources of income, and demographics. The survey was conducted in 1997, 2000, 2004, 2007 and 2010 (corresponding to the 96/97, 99/00, 03/04, and 06/07 crop seasons) and covered 24 administrative districts that included a total of 1,500 original households, of which 1,243 were panel households (after attrition). Out of the national sample, we select an unbalanced panel of 791 households interviewed the last four waves and match criteria described below.

4.1.2 ZAMBIA

The Zambian analysis is drawn from the Supplemental Survey (SS), a nationally representative survey of smallholder farm households in Zambia. The SS is a three-wave panel survey that was conducted in 2001, 2004, and 2008 and contains information on the 1999/2000, 2002/03, and 2006/07 agricultural years. The survey was conducted by The Food and Research

Project of Michigan State University in collaboration with the Central Statistical Office (CSO) and the Ministry of Agriculture and Cooperatives (MACO). The interview was conducted in 70 districts and includes 4,286 panel households. Out of the national sample we select an unbalanced panel of 2,308 households interviewed in 2004 and 2008 based on criteria described below.

4.1.3 MALAWI

Two nationally representative agricultural surveys were used for the Malawi analysis: the Second Integrated Household Survey II (IHS II), and the Agricultural Inputs Support Survey (AISS) I and II.

The first survey, the Second IHS (IHS II), was conducted by the Government of Malawi's National Statistical Office and covers two agricultural years: 2002/03 and 2003/04. A total of 11,280 households from 26 districts were interviewed, with each household being interviewed in one of the two years. The second survey, the AISS, was also conducted by the Government of Malawi's National Statistical Office. Households were interviewed in 2007 and 2009 for AISS I and AISS II regarding the 2006/07 and the 2008/09 growing seasons, respectively. There are 1,375 panel households that are in one of the IHS II (one of the years) and the AISS. Therefore, I use an unbalanced panel of 861 households, with data from the IHS II survey making up panel year 1 in my analysis, and the two years of data from the AISS survey (2007 and 2009) making up panel years 3 and 4 in my analysis, again further refined by criteria described in the sample selection chapter.

4.1.4 Supplemental GIS Climate Data

The household data for all three countries is supplemented by spatial data on rainfall and soil quality. The rainfall and soil quality variables I use are defined for specific point locations that correspond to the households from each of the national household surveys. The rainfall and soil variables were matched with agricultural survey datasets at the district level for all three countries (Kenya, Malawi, and Zambia).

The rainfall and soil data I use come from two geographic information system (GIS) based climate datasets: the CRU TS 3.1 Climate Database and the Harmonized World Soil Database v 1.2. The CRU-TS 3.1 Climate Database was developed by the University of East Anglia in 2011 and includes data from 1901 to 2009 at a spatial resolution of 0.5 decimal degrees. [1] From the CRU TS 3.1 dataset, I draw historical time-series data on rainfall data for each country. The Harmonized World Soil Database (HWSD) v 1.2 is a "30 arc-second raster database with over 16000 different soil mapping units that combines existing regional and national updates of soil information worldwide (SOTER, ESD, Soil Map of China, WISE) with the information contained within the 1:5 000 000 scale FAO-UNESCO Soil Map of the World (FAO, 1971-1981)," as stated on the HWSD website.[2]

4.2 Sample Selection

With the objective of analyzing maize response, fertilizer use and profitability across different countries, I chose to focus on households in Kenya, Malawi, and Zambia for several reasons. First, based on data availability, all three countries have agricultural household surveys available that have been widely used and reviewed, and cover similar topics yielding comparable data. Secondly, these three countries offer an interesting juxtaposition based on the different

[1] Data and more information are available from: http://www.cgiar-csi.org/data/climate/item/104-cru-ts-31-climate-database

[2] The HWSD is available at: http://www.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/
Citation for these data: FAO/IIASA/ISRIC/ISSCAS/JRC, 2012. Harmonized World Soil Database (version 1.2). FAO, Rome, Italy and IIASA, Laxenburg, Austria.

levels and growth rates of maize yield and fertilizer use that they represent, as discussed in the background chapter above. Broadening the scope of this analysis to include fields in three different countries with three different contexts will also provide greater heterogeneity in the sample to more accurately identify the effects of explanatory variables and to link them with differences in agricultural policies and public expenditure patterns in the three countries.

Unlike many studies that use the household as the unit of analysis, I conduct my analysis at the field level. The household surveys used are household panel surveys and not necessarily field panel surveys. However, each year the data used is for the household's largest maize field. I conduct my analysis at the field level using panel methods under the assumption that the household's largest maize field is the same field over the time span of the surveys. Disaggregating to the field level, instead of averaging across fields for household level analysis, increases the accuracy of the findings and opens up different possible topics of analysis. Furthermore, I focus specifically on maize fields given the crops importance in all three countries. The reason for focusing on maize is further discussed in the background information chapter.

While monocropped maize fields do exist, it is very common in Sub Saharan Africa for households to plant more than one type of crop on a field. Therefore, it is possible that many fields are dominated by maize, but may also contain some other crop(s) as well. In order to account for fields that were not were not solely planted with maize but that are dominated by maize, in addition to monocropped maize fields, I also include fields that meet the following criteria:

(1) have maize and no more than six other crops,

(2) does not contain a major cash crop (including include cotton, rice, sugar cane, tea, sisal, pyrethrum, coffee, coffee cherries, and commercial trees), and

(3) maize constitutes at least 25 percent of the field's total potential revenue.

I select and refer to all fields that meet these criteria as "maize fields." This criterion was established by Roy Black, Megan Sheahan, and Thom Jayne in their research on the profitability of fertilizer use on fields in Kenya (Sheahan, M., Black, R., & Jayne, T. S. 2013).

Furthermore, while Zambia and Malawi both have a unimodal maize harvest (April to June) and therefore harvest maize once a year, Kenya has a bimodal maize season with a main crop season (July to September) and a shorter one in (February to April) in the eastern and northern parts of the country. In order to make the results between the three countries comparable, I include only the main season data and drop the data from the shorter season for the fields located in eastern and northern Kenya.

After selecting only maize fields, as defined above, to address challenges associated with outliers, outlier values beyond the 99th percentile were dropped for total household assets, maize yield, quantity of nitrogen applied (kg/ha), quantity of phosphorus applied (kg/ha), and field size (ha). Very small fields can also be an issue by amplifying fertilizer application rates and maize yields and can stem from field measurement error, so I also drop the bottom 1 percent of field size cases. Since household wealth are affected by national specific context, outliers of these values were identified and dropped beyond the 99th percentile within each country dataset, while the top one percent of values of maize yield, quantity of nitrogen and phosphorus applied, and field size were identified and dropped in the pooled, cross-country dataset.

Finally, I further refine my sample by eliminating fields that had a maize yield of 200 kg/ha or less. Since the analysis aims to examine the effects of fertilizer on yield, it is important to consider fields that 1) had a yield, and 2) did not have any other anomalous issues that may have impacted the crop development, as indicated by a “crop failure” with a very low yield below 200 kg/ha. In my sample of fields, approximately 10.6 percent of total fields had a maize yield of or below 200 kg/ha.

Table 4. Prevalence of crop failure among sample				
Mz yield =<200	**Kenya**	**Zambia**	**Malawi**	**Total**
	Freq	Freq	Freq	Freq
	(Percent)	(Percent)	(Percent)	(Percent)
No	2,365	4,910	2,769	10,044
	(95.6)	(96.10)	(74.1)	(88.7)
Yes	110	199	969	1,278
	(4.4)	(3.9)	(25.9)	(11.3)
Total	2475	5109	3738	11322

Given the large size of my sample, excluding fields with a maize yield of 200 kg/ha or less from my analysis still leaves a large sample for regression analysis and I therefore drop these fields from my sample. After dropping fields with crop failure, I am left with the remaining distribution of households in my final sample of 20,686 observations (Table 5).

Table 5. Distribution of final sample fields for regression				
Year	**Kenya**	**Zambia**	**Malawi**	**Total**
1999	501			501
2003	631	2,308	333	3,272
2004			428	428
2006	518			518
2007		2,308	724	3,032
2009	499		424	923
Total	2,149	4,616	1,909	8,674

Chapter 5: Cross Country Production Function Analysis

5.1 Description of Variables and Summary Statistics

Before looking at the econometric analysis, we first look at the variables and summary statistics of all households included in the analysis in order to get a better understanding of the main characteristics of the sample. Table 6 below shows all variables used in the regression analysis.

Table 6. Description of variables used in regression analysis

Variable Type		Variable Name	Description
Y		Mz_yield	Maize yield, kg/ha
X	Continuous	Nitrogen	kg Nitrogen/ha used on maize field
		field_ha	field size (hectares)
		asset	total value of household assets (proxy for hh capital availability)
		rain	cumulative rainfall during planting and growing months (mm)
	Dummy	hybuse	1=use new hybrid seed on filed, 0= did not use hybrid seed on field (used other seed on field (retained hybrid, OPV, local variety))
		mono	1 = monocropped field, 0 = more than 1 crop in the field
		soil_a	nutrient levels in soil: 1- good, 2-moderate, 3-poor
		soil_r	nutrient retention capacity of soil: 1- good, 2-moderate, 3-poor
		Adm1	Kenya = Province; Zambia= Province; Malawi=Regions

Maize yield (Mz_yield) is the output variable in my production function and focus of my analysis. While some studies have used the Liu Myer index, a computed index of yield using maize equivalents of other crops harvested in the same field, as the output variable, I choose to use only maize production given that my interest is the effects of fertilizer use on maize production specifically. Furthermore, since other crops do not respond to fertilizer as much as maize, including other crops in the calculations would compromise the accuracy of my results and cause a downward bias in the estimates of maize response to fertilizer. As shown in Table 7, between the three countries there is a large gap between average maize yield, with Kenya having the highest yield with an average maize yield of 1,975 kg/ha, and Malawi at the low end with an average maize yield of 937 kg/ha, half of that observed in Kenya.

Table 7. Maize yield (kg/ha) by country							
country	**N**	**Mean**	**Percentile**				
			10	**25**	**50**	**75**	**90**
Kenya	2,149	1,975	556	889	1,778	2,667	3,889
Zambia	4,616	1,566	460	714	1,241	2,130	3,067
Malawi	1,909	937	266	403	691	1,152	1,975
Total	8,674	1,529	395	666	1,152	2,130	3,175

Looking at maize trends over time in each country, 2006 stands out as a year with higher yields in Kenya while maize yield was largely consistent over time in both Zambia and Malawi (Table 8). None of the three countries show noticeable increases in yield over the time span of the respective panels, reflecting somewhat stagnant maize yield output over 10 years in Kenya, 4 years in Zambia, and 6 years in Malawi.

Table 8. Maize yield (kg/ha) by country and year								
	year	**N**	**mean**	**p10**	**p25**	**p50**	**p75**	**p90**
Kenya	1999	501	1843	523	889	1481	2667	3704
	2003	631	1951	444	889	1600	2667	4000
	2006	518	2263	741	1200	2000	3111	4148
	2009	499	1838	556	889	1556	2222	3556
	Total	**2149**	**1975**	**556**	**889**	**1778**	**2667**	**3889**
Zambia	2003	2308	1576	460	747	1295	2130	3015
	2007	2308	1555	460	710	1150	2070	3194
	Total	**4616**	**1566**	**460**	**714**	**1241**	**2130**	**3067**
Malawi	2003	333	876	277	395	634	1037	1843
	2004	428	945	292	461	691	1251	1920
	2007	724	942	239	346	636	1152	2074
	2009	424	970	258	461	768	1282	2074
	Total	**1909**	**937**	**266**	**403**	**691**	**1152**	**1975**

Kilograms of nitrogen (Nitrogen) represents fertilizer use in my regression. It is widely documented that nitrogen is a main driver for maize yield across most environments (Vanlauwe B., J. Kihara, P. Chivenge, P. Pypers, R. Coe, J. Six. 2011). Nitrogen is the key driver for cereal crop yield and yield stability across most ecosystems (Vanlauwe B., J. Kihara, P. Chivenge, P. Pypers, R. Coe, J. Six. 2011). Other nutrients are required in modest amounts and only occasionally limit production (Sieg Snapp, T.S. Jayne, Wezi Mhango, Todd Benson and Jacob Ricker-Gilbert 2011).

Furthermore, using a cross-country sample, there are different types of fertilizer used in each country in my sample. Therefore, using quantity (kg) of nitrogen, an input component common to all countries, instead of quantity of inorganic fertilizer allows for cross-country comparison. For these reasons, I calculate total quantity of nitrogen from total inorganic fertilizer applied to the maize field and use quantity of nitrogen applied as the indicator for fertilizer use in my regression analysis. Details on these calculations (using percent of nitrogen and phosphorus found in one kilogram of each type of fertilizer) can be found in Annex Table A.1.

First looking at average fertilizer application rates (kg/ha) on maize fields (as defined for this work in chapter four) across the three countries excluding non-fertilizer users (Table 9), Zambia has by far the highest fertilizer use rate (at 262 kg/ha in 2007), while Kenya and Malawi surprisingly have similar fertilizer application (kg/ha) rates (at 165 kg/ha in 2009 in Kenya, and 168 kg/ha in 2009 in Malawi). However, where as fertilizer application rates stayed nearly unchanged over time in Zambia, rates did increase gradually and slightly in both Kenya and Malawi over the time span of their respective panels (1999 – 2009 in Kenya and 2003 – 2009 in Malawi).

However there are also important variations within each of the countries. In Kenya, Western, Central, and Rift Valley Provinces have the highest fertilizer application rates, while rates are below average and the lowest in the Eastern Province. Over the span of the surveys, fertilizer application rates increased the most (nearly doubling) in Nyanza Province. There is more provincial fertilizer application rate variation in Zambia. Western Province by far has the highest application rates, which is the lowest maize production area, indicating fertilizer application possibly being implemented as a maize production improvement strategy to compensate for other adverse factors in that area. Interestingly, on the other end of the spectrum, the highest producing area, Eastern Province, has the lowest fertilizer application rates in the country, perhaps indicating otherwise favorable conditions in that area. Regional variation in Malawi was significant in the first wave (2003) with a fertilizer application rate of only 87 kg/ha in the South region and 268 kg/ha in the North region, but has narrowed over time to rates of 159 kg/ha and 206 kg/ha, respectively, in 2009 as application rates in the South region nearly doubled between 2003 and 2009. By 2009, application rates in the South region are on par with rates in the Central region.

Table 9. Mean kilograms of fertilizer applied per ha (excluding zeroes)

		1999	2003	2004	2006	2007	2009
Kenya	**National**	**129.0**	**142.9**		**164.7**		**165.3**
	Eastern	114.1	86.09		108.9		128.6
	Nyanza	79.16	102.0		129.6		155.7
	Western	135.3	153.7		165.2		177.4
	Central	127.8	110.5		154.2		172.0
	Rift valley	145.6	167.7		186.7		170.7
Zambia	**National**		**247.4**			**261.7**	
	Central		251.8			280.0	
	Copperbelt		289.6			290.5	
	Eastern		213.6			200.2	
	Luapula		350.2			355.8	
	Lusaka		228.4			293.9	
	Northern		342.6			342.8	
	Northwestern		270.5			280.1	
	Southern		186.9			218.3	
	Western		246.0			419.0	
Malawi	**National**		**128.9**	**103.3**		**173.7**	**168.0**
	North		268.0	159.4		189.8	205.9
	Central		141.2	125.0		174.1	160.8
	South		87.17	70.71		165.4	158.5

When considering fertilizer use rates, or the percent of maize fields with fertilizer applied in each country (Table 10), interestingly Zambia has the lowest percent of fields that had fertilizer applied, with only 40 percent of fields receiving fertilizer application. Kenya and Malawi generally have similar percent of fields with fertilizer use, around 60 – 80 percent. However, in Malawi, the proportion of fields receiving fertilizer application has increased from 63 percent in 2003 to over 80 percent of fields in 2009. The lower application rates and higher proportion of fields receiving fertilizer in Kenya and Malawi, compared to the higher application rates and lower proportion of fields receiving fertilizer application in Zambia, indicate a very different fertilizer access structure among the three countries.

Table 10. Percent of farmers using fertilizer

	Kenya	Zambia	Malawi
Year	**Used Fertilizer**	**Used Fertilizer**	**Used Fertilizer**
1999	68.5		
2003	71.8	37.8	63.4
2004			67.1
2006	78.6		
2007		39.6	74.7
2009	73.4		87.5

Looking specifically at the field nitrogen application rates (kg/ha) again on maize fields, as definied for this work in section four, and excluding non-fertilizer users, as shown in Table 11 the rate of nitrogen applied to fields (kg/ha) is highest in Zambia, followed by Malawi, and lowest in Kenya. Over time (Table 12), average rates have remained fairly constant in Zambia, but increased by around 30 percent in both Kenya and Malawi (between 1999 and 2009, and between 2003 and 2009, respectively).

Table 11. Nitrogen application (kg/ha) by country (without zeroes)							
Country	**N**	**mean**	**Percentile**				
			10	**25**	**50**	**75**	**90**
Kenya	1,569	34.5	8.7	14.8	22.2	54.3	77.6
Zambia	1,785	72.2	22.4	34.6	66.0	112.0	132.1
Malawi	1,410	50.3	8.6	18.9	42.6	71.0	94.7
Total	4,764	53.3	11.1	22.2	42.8	74.7	112.0

Table 12. Nitrogen application (kg/ha) by country and year (without zeroes)					
	Obs	Mean	Std.Dev.	Min	Max
Kenya					
1999	343	29.1	25.1	0.7	146.9
2003	453	33.1	26.6	0.0	129.6
2006	407	38.0	27.4	1.8	151.2
2009	366	37.5	25.5	0.0	121.0
Zambia					
2003	872	69.9	47.2	0.9	224.0
2007	913	74.4	43.6	5.0	224.0
Malawi					
2003	211	41.9	36.2	1.3	170.4
2004	287	33.6	31.6	1.7	170.4
2007	541	58.7	43.1	0.1	213.0
2009	371	55.6	36.2	3.0	170.4

Phosphorus is another important nutrient in inorganic fertilizers However, whereas applied nitrogen (via fertilizers) is used by plants that same season (more immediately), phosphorus is a less mobile nutrient. As a result, plants only absorb about 20 percent of applied phosphorus in the first year (Griffith, B. n.d.), making it important for more long-term soil nutrient levels. This makes it difficult to model yield response to phosphorus (Lanzer, E. A., & Paris, Q. 1981). Furthermore, many studies have found high collinearity between nitrogen and phosphorus (Megan Britney Sheahan 2011). Given its collinearity with nitrogen and the difficulty in estimating the response to phosphorus based on its characteristics, I do not include phosphorus as a variable in the production function directly as a standalone variable, but instead include the effects of applied phosphorus on maize response by stratifying my regression estimation by a ratio of applied phosphorus to nitrogen. This will be discussed later on.

Hybrid seed use (hybuse) is a well-documented part of input use and maize yield research for Sub-Saharan Africa. Hybrid seeds have proven to be more effective than local seed, even when planted without fertilizer (Smale, M and P. Heisey 1997). Hybrid maize (and open-pollinated varieties) is estimated to have covered 44 percent of maize area in Eastern and Southern Africa in 2006/7 (not including South Africa). New hybrid seed variety release grew quickly between 2002 and 2006 in SSA, with the highest rates in Kenya, Malawi, and Zambia, along with Zimbabwe (Melinda Smale, Derek Byerlee, Thom Jayne 2011).

Given the distinct dichotomous difference in effects of hybrid seeds versus all other non-hybrid seeds (OPV, recycled hybrids, and local seeds), I include hybrid seed use in my analysis as a dummy variable. At the national level, Kenya has the highest percent of fields with hybrid seeds applied, followed by Malawi, and then Zambia (Table 13). Within Kenya, similar to fertilizer use trends, Rift Valley, Western, and Central Provinces have the highest hybrid seed use, while the Nyanza Province has the lowest. Contrary to domestic fertilizer use trends in Zambia, Lusaka Province has the highest hybrid seed use (while also have the lowest fertilizer use trends), while Eastern Province, like the fertilizer trends, has the lowest use in the country. Finally, in Malawi, following fertilizer trends, the North region has the highest hybrid use, with similar hybrid use observed in Central and South regions. Also parallel to the fertilizer use rates, hybrid seed application increased the most in the South region of Malawi over the span of the surveyed time period.

Table 13. Percent of fields using hybrid seeds by adm1 and year							
Country	**Level**	**1999**	**2003**	**2004**	**2006**	**2007**	**2009**
Kenya	**National**	**76.5**	**70.4**		**80.3**		**83.0**
	Eastern	52.4	45.2		66.7		74.6
	Nyanza	67.3	47.1		56.9		59.7
	Western	76.1	72.2		82.4		89.8
	Central	73.7	57.1		68.8		83.3
	Rift valley	91.4	93.3		94.8		96.4
Zambia	**National**		**41.2**			**43.2**	
	Central		63.5			73.3	
	Copperbelt		54.0			62.0	
	Eastern		14.8			14.9	
	Luapula		51.4			48.7	
	Lusaka		66.3			74.2	
	Northern		38.0			41.2	
	Northwestern		14.9			27.7	
	Southern		72.7			70.9	
	Western		39.8			26.9	
Malawi	**National**		**46.6**	**54.9**		**57.6**	**51.2**
	North		56.1	56.0		73.0	58.5
	Central		54.8	55.0		66.7	48.8
	South		39.3	54.4		47.2	49.6

Self-reported area of each plot in hectares were used for **field size** (field_ha). The distribution of field size of the sample is shown below in Table 14. Overall, the smallest two quintiles make up the majority (approximately 50 percent) of all fields. While Kenya and Malawi follow this trend, Zambia shows the opposite trend where the largest two quintiles represent the largest proportions of fields. Field size is more skewed in Malawi and Kenya, with the smallest field size quintiles representing around 60 percent of fields in each panel year, while field size in Zambia is more evenly distributed. Furthermore, field size structure in Malawi appears to have shifted over time with the two largest field size quintiles shrinking over time, and the two smallest field size quintiles representing an increasing proportion of fields in the country over time.

Table 14. Distribution of Field size					
Percent of fields in Field size quintiles by Country and year					
	1	**2**	**3**	**4**	**5**
	0.5 - 1 ha	**1.01 - 2 ha**	**2.01 – 3 ha**	**3.01 - 4 ha**	**4.01 - 5 ha**
Kenya	30.2	29.2	10.6	13.3	16.8
1999	25.8	26.4	12.6	14.0	21.4
2003	29.5	29.5	11.4	14.9	14.7
2006	32.8	28.2	10.4	9.5	19.1
2009	32.7	32.7	7.6	14.6	12.4
Zambia	16.3	16.6	18.8	24.3	23.9
2003	18.9	16.5	17.6	25.0	22.1
2007	13.8	16.8	20.0	23.6	25.8
Malawi	22.3	38.7	12.5	17.0	9.6
2003	17.4	40.2	10.5	24.3	7.5
2004	18.9	39.7	15.9	18.9	6.5
2007	17.5	37.3	12.4	18.1	14.6
2009	37.5	38.9	10.6	7.3	5.7
Total	26.9	23.3	12.3	20.3	17.2

Monocropped or intercropped (mono)- In order to control for the effects of the presence of other crops in the same field as maize, a dummy variable representing mono-cropped maize or not (representing inter-cropped; maize planted in the same field with other crops) is included as a control.

Zambia maize fields in my sample are strongly dominated by monocropped planting schemes, while Kenya and Malawi have a more diverse maize field crop structure. In Malawi, the majority of maize fields are either monocropped or have maize and one other crop (two crops total), while in Kenya the majority of the fields have two to three crops.

Table 15. Percent of fields by number of crops in field and country							
	Monocropped	**Intercropped**					
Country	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Kenya	3.9	21.6	34.2	14.2	11.6	8.8	5.6
Zambia	96.0	3.8	0.2				
Malawi	34.7	32.2	21.4	7.8	3.9		
Total	59.7	14.5	13.3	5.3	3.8	2.2	1.4

To capture variation in local production climates, I include measures of rainfall during the appropriate planting and growing months, soil nutrient availability, and soil nutrient retention capacity. Rainfall in Africa is much lower than other parts of the world, averaging 12.5 cm/year compared the world average of 24.9 (when calculated as precipitation minus evaporation) (Brady, N. 1990). **Rainfall** (rain) is calculated as the cumulative rainfall during the planting and growing months of the relevant agricultural year. The planting and growing periods correspond to different months in Kenya, Malawi, and Zambia. The planting and growing months as defined for this analysis for each country are presented in Table 16.

Table 16. Growing and planting months by admin 1

Country	Province	Growing and planting months
Kenya	Eastern	March to June
	Western, Coast, and Central	April - June
	Valley	April – October
Malawi	all	November – March
Zambia	all	November – March

At the national level over time, Malawi actually received, on average, the greatest amount of rainfall with 1,248 mm of rain during its planting and growing months. On the other end of the spectrum, the average rainfall during the planting and growing months in Kenya was nearly half of the average in Malawi, at 650 mm of rainfall (Table 17).

Table 17. Rainfall (mm) by country

Country	N	mean	Percentile				
			10	25	50	75	90
Kenya	2149	650.8	323.7	433.4	659.0	872.1	994.1
Zambia	4616	1052.0	728.6	848.0	1070.0	1209.0	1352.0
Malawi	1909	1248.0	887.0	981.7	1116.0	1515.0	1737.0
Total	8674	995.6	512.9	775.2	1005.0	1182.0	1419.0

Disaggregating by year and admin1 level (province for Kenya and Zambia, region for Malawi), it is clear that these rainfall patterns vary greatly within each country (Table 18). In Kenya, Rift Valley Province received the most rain, and Eastern Province received the least rain. In Zambia, Eastern, Copperbelt, and Northern Provinces typically received higher rainfall during the planting and growing months, while Western and Southern Provinces received the least. Finally, domestic rainfall trends varied in Malawi, with the North receiving the most rainfall in 2003 and 2004, but then reversing and receiving the least rainfall (with Central and South receiving more) in 2007 and 2009. The Central and South regions seem to follow similar rainfall patterns, while North region has a different rainfall trend.

Table 18. Mean rainfall during planting and growing months (mm)

		1999	**2003**	**2004**	**2006**	**2007**	**2009**
Kenya	National	477.6	892.9		629.7		654.4
	Eastern	287.3	460.6		409.0		271.7
	Nyanza	332.8	677.5		408.9		513.4
	Western	508.7	823.9		512.5		645.6
	Central	324.5	823.0		562.0		547.6
	Rift valley	630.1	984.8		902.6		913.9
Zambia	National		1067.0			1036.0	
	Central		1237.0			937.4	
	Copperbelt		1578.0			1186.0	
	Eastern		1052.0			1238.0	
	Luapula		1266.0			1124.0	
	Lusaka		999.2			803.8	
	Northern		1206.0			1174.0	
	Northwestern		1196.0			1081.0	
	Southern		716.9			730.9	
	Western		747.6			782.6	
Malawi	National		962.8	1039.0		1591.0	1096.0
	North		1069.0	1067.0		1234.0	976.6
	Central		957.1	1008.0		1735.0	1123.0
	South		927.3	1038.0		1697.0	1125.0

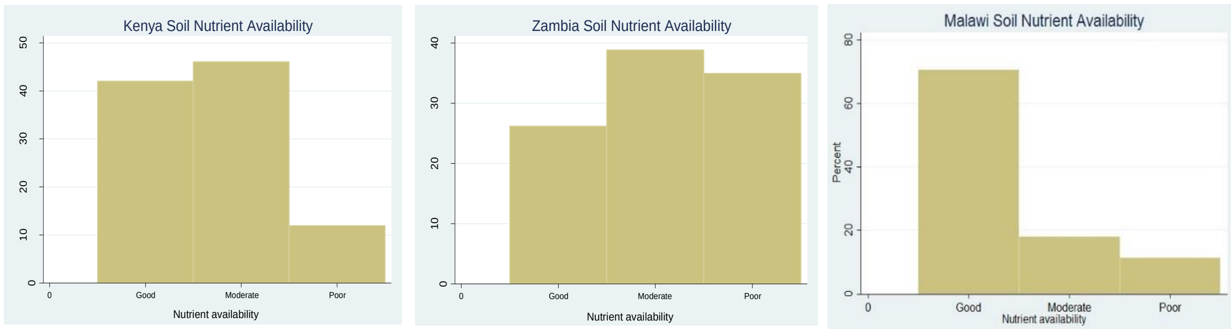
Soil characteristics (soil_a and soil_r) – Although there are several characteristics that distinguish soils, Bauer and Black found that available nutrients and soil fertility (soil organic matter) drive productivity (A. Bauer, A. L. Black 1994). Soil fertility degradation is argued to be the "most fundamental impediment to agricultural growth and a major reason for decreasing trends in food production in SSA" (David Yanggen, Valerie Kelly, Thomas Reardon, and Anawar Naseem 1998). "Acid infertile soils" (oxisols and ultisols) make up 56% of all African soils; "very infertile sandy soils" (psamments) make up 16%; "poorly drained soils" (aquepts) make up 12% of African soils. Totaling 84% of all African soils, most of the soil in Africa is either infertile or poorly drained. Only 12% of all African soils fall into the category of "moderately fertile, well-drained soils" (including alfisols, vertisols, mollisols, andepts, tropepts, and fluvents), which make up 33% of Asian soils (David Yanggen, Valerie Kelly, Thomas Reardon, and Anawar Naseem 1998).

From the Harmonized World Soil Database I pull two soil variables to represent soil quality; soil nutrient availability, and soil nutrient retention capacity. Both variables are constructed from a variety of soil quality measures. Soil nutrient availability includes measures of soil texture, soil organic carbon, soil pH, total exchangeable bases currently present or available in the soil. This reflects the overall current quality of the soil. The second soil variable, soil nutrient retention capacity, reflects the capacity of the soil to absorb and retain additional nutrients and includes measures of soil organic carbon, soil texture, base saturation, cation exchange capacity of soil and of clay fraction. This is important because a soil that may have current high levels of nutrients, but may not be fit to absorb nutrients, meaning it may not react to applied nutrients and, furthermore, its nutrient levels will deplete over time. In the Harmonized World Soil Database these variables are given as categorical variables ranging 1 to

6, corresponding to receding levels of quality, with 1 being the highest quality and 6 the lowest. After merging with my dataset at the provincial or regional level (admin 1) and analyzing the distribution, categories 1 through 3 represented 99 percent of all fields in my dataset for both soil variables. Given this collinearity, I drop cases with soil variable values of 4, 5, and 6 (1 percent of all cases). I then create dummy variables for each of the remaining categories (1, 2 and 3) for each of the two soil variables. I do not include category 1 (good quality) dummy variable in the regressions, and do include categories 2 (moderate quality) and 3 (poor quality) dummy variables in the regression. I also interact these two dummy variables with kilograms of nitrogen to investigate if the effect of nitrogen application on maize response depends on the quality of soil, and vice versa.

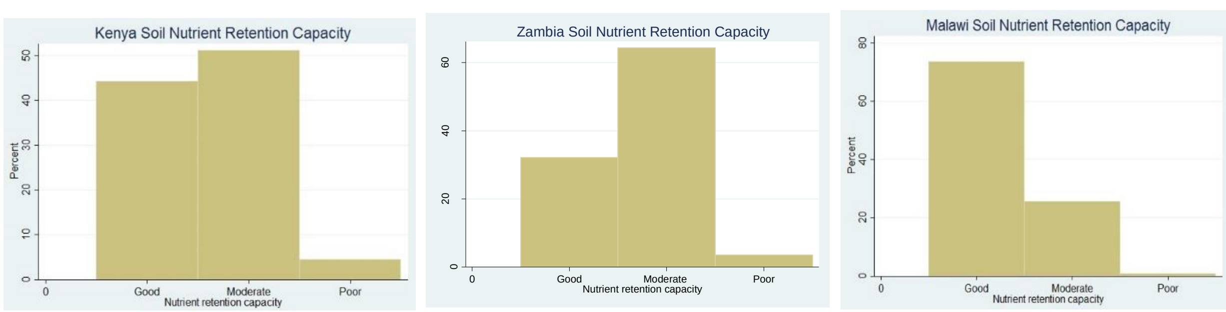
As shown in Figures 5 and 6 each of the three countries has different soil quality trends. While moderate nutrient availability is the dominant soil groups in Kenya and Zambia (covering approximately 45 percent of soil in Kenya and nearly 40 percent of soil in Zambia), the majority of soils in Malawi have good nutrient availability (over 60 percent of all soil). However, in Zambia, the second largest group of soils is the poor soil nutrient availability group (over 30 percent of soil), while the second largest group in Kenya is good nutrient availability (over 40 percent of soil). Both Kenya and Malawi have approximately 90 percent of all soil containing good or moderate nutrient levels, in Zambia only about 60 percent of all soil has good or moderate nutrient levels.

Figure 5. Soil Nutrient Availability by Country



Soil nutrient retention capacity (Figure 6) generally follow the same trends in each country. One difference is that all three countries have a lower proportion of "poor" levels present, meaning soil nutrient retention capacity is higher than the current levels of nutrients. Although all three countries are similar on this measure, Malawi has the highest proportion of good to moderate soil nutrient retention capacity.

Figure 6. Soil Nutrient Retention Capacity by Country



As a proxy for household capital, I look at **household assets** (asset). Given the presence of three different currencies and ten years of values, I adjust for inflation and convert all values to USD, and compare assets in real USD terms. Table 19 shows that there is a huge gap between the average level of household assets in Kenya, at the high end, and Malawi, at the low end. This is in line with the macroeconomic indicators that reflect a much lower GDP in Malawi, as one of the poorest countries in Africa. However, it also must be noted that these values are self-reported values and come free three different surveys that are not identical. Therefore, while these values offer a measure of relative comparison, it must be noted that they may not be the exact same measure.

Table 19. Summary of assets by country							
Country	**N**	**mean**	**p10**	**p25**	**p50**	**p75**	**p90**
Kenya	2149	3.75	0.36	0.72	1.530	3.68	9.37
Zambia	4616	0.73	0.0	0.01	0.08	0.62	2.37
Malawi	1909	0.26	0.02	0.04	0.11	0.25	0.59
Total	8674	1.38	0.0	0.04	0.20	1.21	3.44

Province or Region (admin_1) dummy variables are included to reflect the differences in maize yield, and effects of fertilizer on maize yield, between Kenya, Malawi, and Zambia that is an important focus of this analysis. These dummy variables also serve to capture all other effects not accounted for in other variables. Admin 1 level corresponds to provinces in Kenya (8) and Zambia (7), and regions in Malawi (3). Table 20 shows the number of observations (fields) in each admin 1 for each year of data.

Table 20. Number of observations (fields) by admin 1 and year								
Country	**Admin 1**	**1999**	**2003**	**2004**	**2006**	**2007**	**2009**	**Total**
Kenya	Eastern	63	73		39		63	238
	Nyanza	110	138		102		114	464
	Western	134	205		170		137	646
	Central	19	7		16		18	60
	Rift valley	175	208		191		167	741
Zambia	Central		315			315		167
	Copperbelt		200			200		630
	Eastern		730			730		400
	Luapula		37			37		1,460
	Lusaka		89			89		74
	Northern		221			221		178
	Northwestern		141			141		442
	Southern		374			374		282
	Western		201			201		748
Malawi	North		66	109		178	82	402
	Central		84	91		150	82	435
	South		183	228		396	260	407
Total		**501**	**3,272**	**428**	**518**	**3,032**	**923**	**8,674**

5.2 Model Specification and Testing

I build a modified quadratic crop response function based on conceptual or theoretical support for important indicators and interactions, along with availability of data in all three different country household surveys. As part of building my model, I run several diagnostic tests to examine variation, multicollinearity, homoscedasticity, and presence of unobserved household heterogeneity.

Sufficient variation across variables is needed for estimation. Table A.2 in the Appendix shows that the standard deviations overall, between households in a given time, and at the household level over time (within) for my total sample, and by PN ratio group, are high, indicating there is sufficient variation for estimation of my total sample and disaggregated by PN ratio groups. Furthermore, the standard deviations show that there is sufficient variability within farms with respect to the inputs that are not time constant (such as nitrogen use) to use the within CRE estimator, and sufficient variability between farms with respect to the time constant measures (such as soil quality) to estimate their effect.

I also test for multicollinearity and find a moderate level of multicollinearity among my parameters, as indicated with a moderately high vif and condition score. However, the main parameters that have high multicollinearity are interactions with nitrogen and nitrogen squared. Since we expect nitrogen and nitrogen squared terms to be related, and to the extent that the high condition score for these variables seem to be increasing the overall condition score, we are not concerned with the overall mulitcollinearity of the model.

Thirdly, I use a Breusch-Pagan method to test the homoscedasticity assumption. The results of this test are significant, indicating heteroskedasticity, or rather that we can reject the null hypothesis of homoscedasticity. Heteroskedasticity is common in large samples and is typically addressed by using the robust option for estimation. Finally, I use a Wald test to test for the appropriateness of estimating with CRE using the Mundlak-Chamberlain device to estimate parameters of variables that are time constant and to control for correlation between unobserved effects and observed independent variables. The p-value of my Wald test is significant, indicating that the means of the time-variant variables are significant and that my model does include unobserved household effects that are correlated with other explanatory variables. Therefore, the CRE model with the Mundlak-Chamberlain device is the most appropriate estimation method in order to control for these effects, allow for estimation of time invariant variables, and produce unbiased estimates for my sample.

Since I pool the three panel data sets from the three countries, the resulting panel that I use for regression is unbalanced. My resulting model is as follows:

$$
\begin{aligned}
Y_{ijt} = \; & a_1 + B_1 N_{ijt} + B_2 N_{ijt}^2 + B_3 Moderate\_soilnut_{ijt} + B_4 Poor\_soilnut_{ijt} \\
& + B_5 Moderate\_soilCap_{ijt} + B_6 Poor\_soilCap_{ijt} + B_7 N_{ijt} * Moderate\_soilnut_{ijt} \\
& + B_8 N_{ijt} * Poor\_soilnut_{ijt} + B_9 N_{ijt} * Moderate\_soilCap_{ijt} + B_{10} N_{ijt} \\
& * Poor\_soilCap_{ijt} + B_{11} N_{ijt}^2 * Moderate\_soilnut_{ijt} + B_{12} N_{ijt}^2 * Poor\_soilnut_{ijt} \\
& + B_{13} N_{ijt}^2 * Moderate\_soilCap_{ijt} + B_{14} N_{ijt}^2 * Poor\_soilCap_{ijt} + B_{15} rain_{ijt} \\
& + B_{16} N_{ijt} * rain_{ijt} + B_{17} hybrid_{ijt} + B_{18} N_{ijt} * hybrid_{ijt} + B_{19} hect_{ijt} + B_{20} hect_{ijt}^2 \\
& + B_{21} asset_{ijt} + B_{22} asset_{ijt}^2 + B_{23} mono_{ijt} + B_{24} adm1_{ijt} + c_j + \mu_{ijt}
\end{aligned}
$$

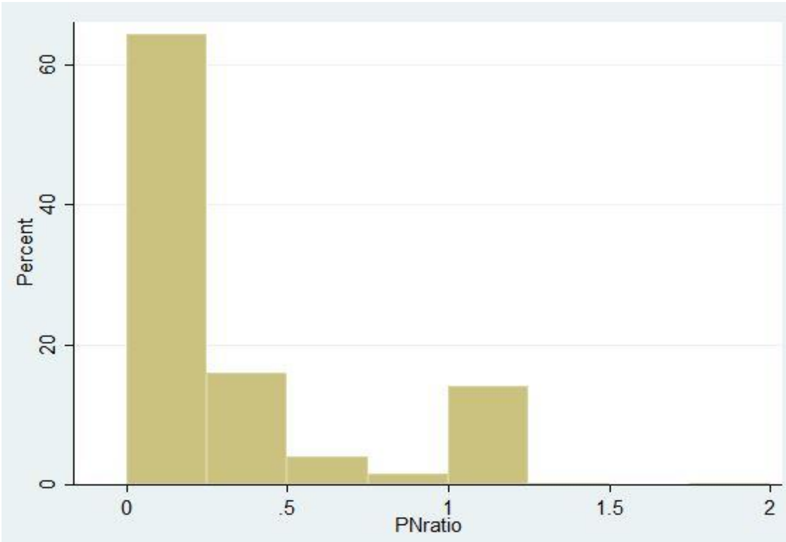
Where c_j represents the Mundlak-Chamberlain device. Variables that vary by field, household, and year include nitrogen, hybrid seed use, field size (hect), and monocropped (mono). Variables that vary by household and year include rainfall, and assets. Variables that are constant over time are soil nutrients level (soilnut), soil nutrient retention capacity (soilCap), and admin 1 from all countries (province or region depending on the country).

For the regressions, I omit the following dummy variables: good soil nutrient level dummy, N*good soil nutrient, good soil nutrient retention capacity, N*good soil nutrient retention capacity, and admin 1_6 (rift valley province dummy).

Finally, due to a high correlation between nitrogen and phosphorus, I include nitrogen use only in my model. However, although other studies that focus on fertilizer use within one country, or even a subregion of a country, in Africa are limited by homogenous fertilizer use among their sample as a result of the limited fertilizer markets in Africa (as discussed above), the inclusion of three different countries in my sample allows for variety of fertilizer types, and therefore, variation of ratios of applied nitrogen and phosphorus between fields and across time. Recognizing that the ratio between nitrogen and phosphorus varies across households greatly depending on the type of fertilizer(s) applied and that the ratio between those nutrients may be a key component of fertilizers effect on yield, I stratify my sample by the phosphorus to nitrogen ratio (PN ratio) into three groups.

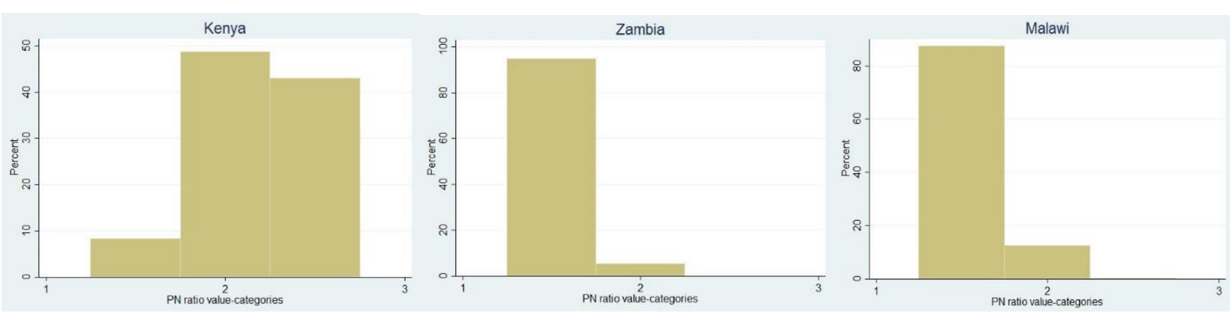
Producing a histogram of the distribution of PN ratio among my total sample reveals three major different groups of PN ratio values: 0 -.24, .25 - .29, and above 1, as shown in Figure 6 below.

Figure 7. Phosphorus:Nitrogen ratio distribution



I therefore stratify my sample by these three PN ratio groups and run three separate estimations, one for each PN ratio group. When looking at the breakdown of PN ratio by country, it is interesting to see there are two different distribution trends. Most households in Kenya applied fertilizer with the higher PN ratio values (.25 - .99 category, and 1 or more category), indicating application of higher phosphorus content. In contrast to Zambia and Malawi where the majority of households applied fertilizer with the lowest PN ratio value (0 -.24).

Figure 8. Phosphorus:Nitrogen ratio group by Country



Looking at the PN ratio trend in each country over time, it is clear that the trends have remained fairly stable except in Kenya. Between 1999 and 2003 there is a change in the distribution patter of PN ratio of fertilizers applied in Kenya. In 1999, the highest PN ratio group

(PN value of 1 or more) was the most prevalent, followed by the second highest PN ratio group, and then the lowest PN ratio group as the smallest proportion of fertilizer application. In 2003 however, the pattern changes a little bit, as the proportion of farmers using fertilizer in the middle PN ratio group increased to become the most prevalent, and the highest PN ratio group decreased to become the second most used PN ratio value. This trend hold for the following two waves in 2006 and 2009. In Zambia and Malawi, the lowest PN ratio group was consistently the largest group, followed by the middle PN ratio group, across all survey years.

Figure 9. Kenya Phosphorus:Nitrogen ratio group by year

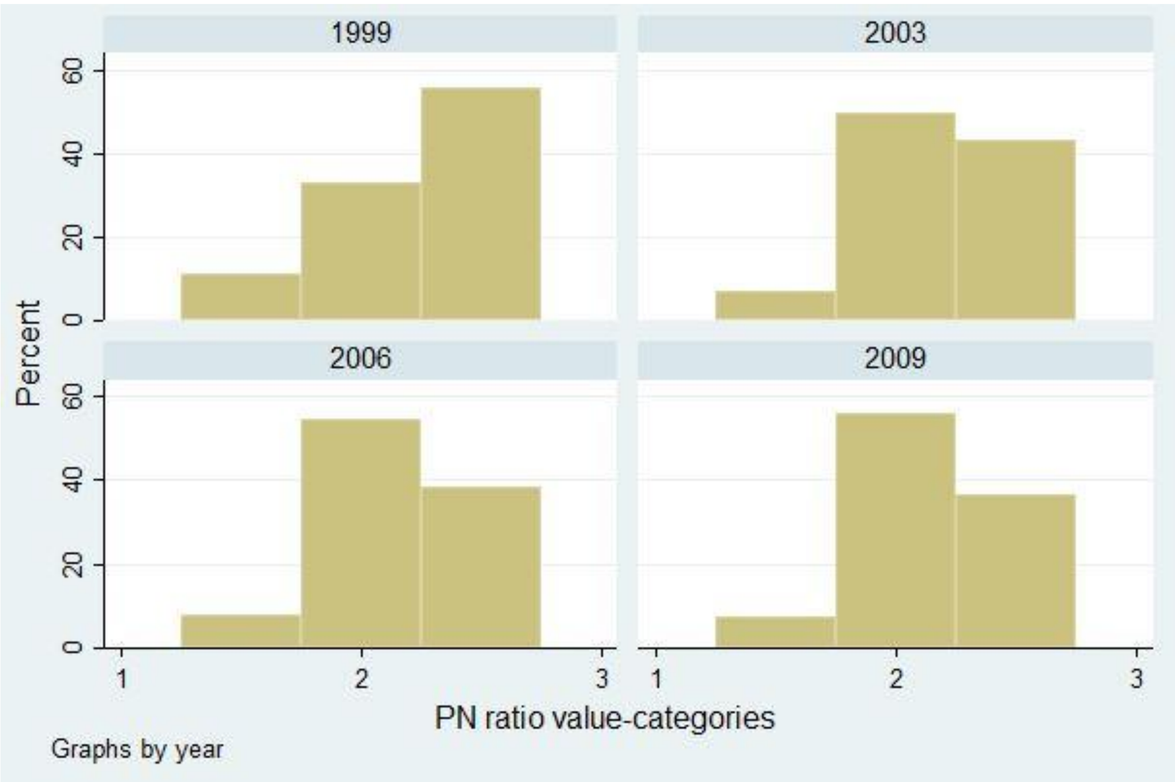


Figure 10. Zambia Phosphorus:Nitrogen ratio group by year

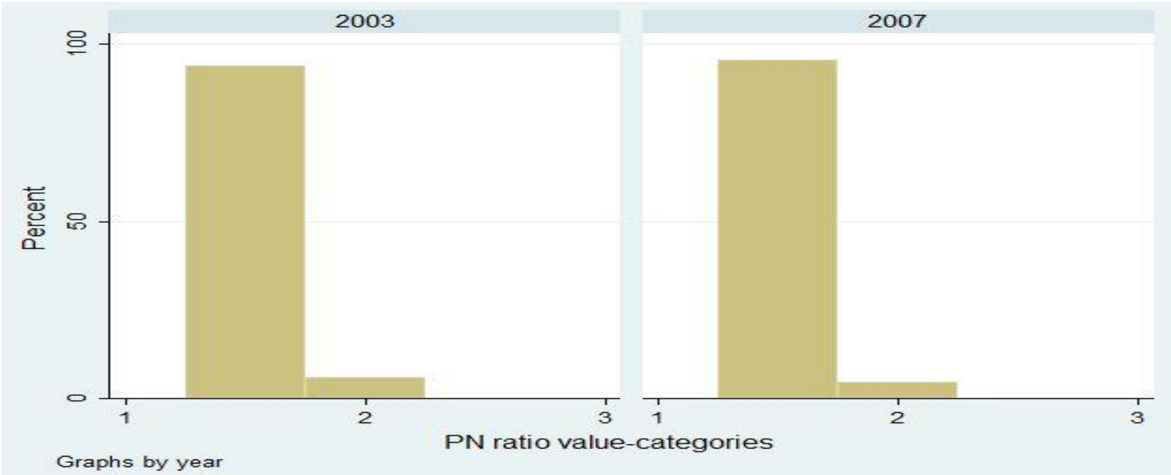
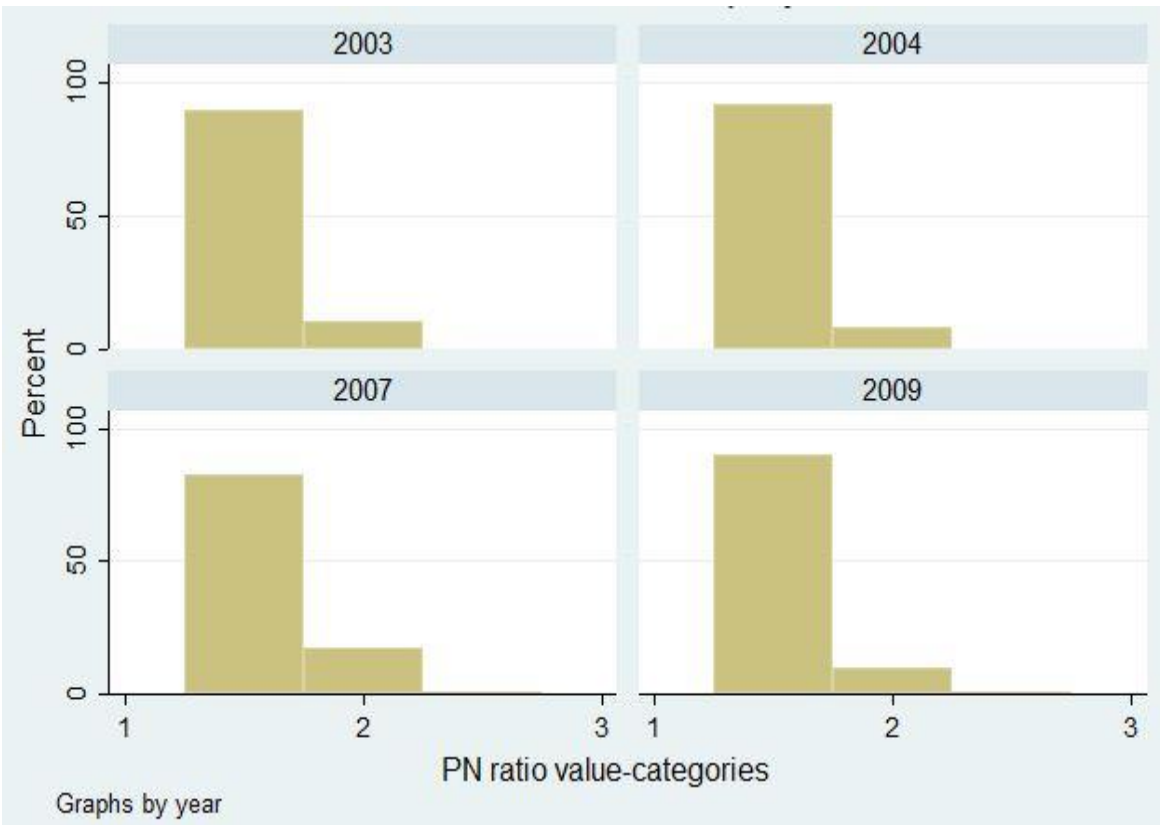


Figure 11. Malawi Phosphorus:Nitrogen ratio group by year



5.3 Regression Results

First I estimate the regression using OLS, Correlated Random Effects (CRE), and Fixed Effects (FE) to compare across methods. The appropriateness of the quadratic functional form is confirmed by the significance of squared terms, including household assets and field size, which will be discussed later, allowing for concavity. The significance of the Mundlak-Chamberlain device variables indicates the importance of using the CRE approach in order to estimate effects of the time invariant variables and control for correlation between unobserved effects and observed explanatory variables. As mentioned above, I use the CRE results for my maize response analysis, and subsequent fertilizer profitability analysis. From here forward, results of the CRE estimation will be the focus of discussion for maize response. I run the regression first across the entire sample, and then stratified by PN ratio group. I will first discuss the aggregate estimation results, and then stratified estimation results.

As seen in Table A3 the coefficient on nitrogen is approximately 10 and statistically very significant. In addition to the nitrogen variable, the interaction between nitrogen and rainfall is significant and unexpectedly negative but the magnitude is very small. Rainfall alone is not significant, which is not a surprising finding. Capturing total rainfall alone excludes other important aspects of rainfall that play a role in maize production and growth. Intense storms in Africa restrict the capacity of crops to fully use rain water and contributes to high levels of soil erosion (Lal, R. 1990).

Hybrid seed use has a large, positive, and significant coefficient, which is in line with other research and expected (Z. Xu et al. 2009; Megan Britney Sheahan 2011). The interaction between hybrid seed use and nitrogen is not significant, however. This is surprising but may be the result of high collinearity between fertilizer use and hybrid seed use.

Field size and field size squared are both significant with opposite signs: field size is negative, decreasing maize yield significantly, while field size squared is positive, meaning field size has an increasing relationship with maize yield. This is consistent with Megan Sheahan's findings. Household assets exhibit a significant positive but diminishing return relationship, which is in line with other research. The Mundlak-Chamberlain (MC) averaged asset squared term is also significant.

Monocropped maize is not significant, however the MC averaged monocropped variable is significant and positive, indicating the presence of unobserved household level heterogeneity and verifying of the importance of controlling for those consequences using the MC approach.

For the soil variables, both the moderate and poor soil nutrient level dummies are negative and significant, indicating that maize yield is lower in soils that have poor or moderate levels of nutrients compared to yields in soil that have good levels of nutrients, which is expected. For soil nutrient retention capacity, the moderate level dummy is not significant, while the poor soil nutrient retention capacity is unexpectedly positive, significant, and large, implying that maize yield is higher in soils that are not able to retain nutrients well. This could be reflecting farmer response behavior to poor soils. Studies have found that rainfall variability effects on soil nutrient uptake efficiency influences farmers' fertilizer strategies (Bationo, A. 1998; Brouwer, J., and J. Bouma. 1997).

Soil dummy variables interacted with nitrogen are not significant, which indicates that nitrogen response does not vary with current nutrient levels of the soil, or the capacity of the soil to retain additional or new nutrients. These results are contradictory to expectations and may be the result of poor indicator composition. It is likely that the variable is not capturing the intended underlying concept, which is a limitation of these findings.

All of the admin 1 dummy variables are significant, indicating there is spatial variation that differentiates maize response between areas that is not being taken into account in the other variables in the model. All admin 1 dummies from all countries have negative coefficients, as would be expected given that the omitted admin1 dummy is the Rift Valley Province of Kenya, which is the highest producing area of Kenya, and higher producing in comparison to areas of Zambia and Malawi as well. These results are quite powerful and in line with expectations.

Next I run a stratified CRE regression by PN ratio group. As explained before, I divide the sample by PN ratio value into three groups: group 1 with a PN ratio value of 0 to .24, group 2 with a PN ratio value of .25 to .99, and group three with a PN ratio value of 1 or more. Running the regression of the sample stratified by PN ratio value allows us to see if the effects of each variable on maize yield vary based on type of fertilizer used by the farmer. This question has been posed by many researchers but has remained largely unanswered and a gap in the literature since most studies focus on sample from one country which does not offer enough variation of fertilizer type, and therefore PN ratio values, to be useful in examining this dynamic. With three countries in my analysis, there is enough variation of PN ratio values to use in my regression analysis. Finally, stratifying my regression by PN ratio value allows phosphorus, the second most important component in fertilizer (after nitrogen), to play a role in my regression.

Based on the regression results (Table A3), the coefficient on nitrogen (kg/ha) is significant for all three PN ratio groups and increases in magnitude with PN ratio. The coefficient is 9.7 for PN ratio group 1 (PN ratio of 0 - .24), 27.4 for the PN ratio group 2 (PN ratio of .25-.99), and highest for PN ratio group 3 (PN ratio of 1 or more) with a coefficient of 58.5. This is a useful finding because it provides evidence that a lower phosphorus to nitrogen ratio used in fertilizer is a more productive input for maize production, and applying fertilizer with a phosphorus to nitrogen ratio of 1 or more is not having the desired yield enhancing effects.

Rainfall is unexpectedly significant and negative for the lowest two PN ratio groups, however at very small magnitudes. Hybrid seed use is only significant for PN ratio group 2 (PN ratio of .25 - .99) with a value of 520. The interaction between nitrogen and hybrid use is also significant for the middle PN ratio group but is unexpectedly negative. This may indicate that either nitrogen use is excessive in the sample or that other factors may be present that are having an impact on this relationship.

Field size is only significant for PN group 1 and show the same relationship as in the aggregated CRE estimates. Although the monocropped dummy was not significant in the aggregate regression estimates, it is significant in the PN ratio stratified regressions for PN ratio group 1 with a negative relationship, reflecting the positive benefits to maize yield when planting maize alongside other crops, particularly legumes. Household assets are not significant for any PN ratio group.

The soil dummy coefficients are interesting. While the soil nutrient level and soil nutrient retention level dummies alone (representing moderate level and poor level of nutrients) are not significant, some interactions with nitrogen are. This reveals interesting information about how differences in soil quality can impact the effects that nutrients (fertilizer) being added to the soil can have on maize yield.

The interaction between nitrogen and both the poor soil nutrient retention dummy and the moderate soil nutrient retention dummy are significant for PN ratio group 3 (PN ratio of 1 or above) and are is positive. The interaction with the poor soil nutrient retention dummy has a greater positive value than that of the moderate soil nutrient dummy interaction. Furthermore, the poor soil nutrient retention dummy interaction is significant and negative for PN ratio group 1 (PN ratio of less than .25). Taking these findings together seems to indicate a positive impact of adding phosphorus to soils that have poor soil nutrient retention capacity.

The poor soil nutrient retention dummy interaction with nitrogen squared is also significant for PN ratio groups 1 and 3 again with reverse signs: positive for PN ratio group 1 indicating an increasing return, and negative for PN ratio group indicating a diminishing return.

Kenya's admin 1 dummy variables are generally each significant for different PN groups. While Eastern Province is significant for PN ratio group 1, Western is only significant for PN ratio group 2, Central only for PN ratio group 3, and Nyanza is significant for all three PN ratio groups. All are negative coefficients. In Zambia, the results are little more consistent with very significant coefficients for nearly all admin 1 dummy variables for the PN ratio group 2 (.25 - .99). Admin 1 dummies in Malawi are significant for PN groups 2 and 3 and are also all negative. Coefficients for PN ratio group 2 are more negative than those for PN ratio group 1. Where there are cases of PN ratio group 3, in Southern Malawi, the coefficient is also significant and negative.

Chapter 6: Cross-Country Fertilizer Profitability Analysis

6.1 MVCR Components

As described in chapter three, there are three main components of the value cost ratio: the marginal or average physical product, the input price of fertilizer (nitrogen), and the output price of maize. Here I go into further detail on the methods I used to calculate each of these three components that I then use to derive the marginal value cost ratio (MVCR) and the average value cost ratio (AVCR).

I calculate the marginal physical product (MPP) and average physical product (APP) of nitrogen at the admin1 level, which is provinces in Kenya and Zambia, and regions in Malawi, and by year. As described above, the MPP of nitrogen is calculated as a weighted average (based on probability of "normal harvest" and "crop failure") of the partial derivative of maize production function with respect to nitrogen. The MPP reflects the extra amount of output (maize) that can be produced by using one additional unit of input (nitrogen), all else held constant. The APP of nitrogen is also calculated as a weighted average (based on probability of "normal harvest" and "crop failure") of the change in the amount of output (maize) as a result of using input (nitrogen) per unit of input (nitrogen) used. This calculation of APP reflects the yield per unit of input (nitrogen) gained relative to not using any input.

For the input price of fertilizer, since applied fertilizer is represented by its main nutrient component, nitrogen, in the production function and the MPP and APP are calculated for nitrogen, I do the same for the input price calculation. I compute the price of nitrogen at the field level using the actual price paid by the household for fertilizer, and then apply the same conversion factors to the price of fertilizer to compute the price of nitrogen that were used to compute kilograms of nitrogen in each respective fertilizer (Table A.1 in the Annex). To reduce the effects of variability in prices paid by households and household level measurement error, I average the price of nitrogen at the district level.

The output price of maize and input price of fertilizer are calculated as admin 2 level (districts in all three countries) averages of all observed values for each respective year.[3] These prices represent the actual price received by the household for selling their maize, and actual price paid by the household for fertilizer they purchased. It is important to note that these prices do not include other costs that go into the final price for maize or fertilizer for a household, such as transport costs to bring the maize or fertilizer from the market to their house. Therefore, total actual cost of maize and fertilizer to households may vary depending on these other cost elements that are not available in my data.

Secondly, in Malawi, the fertilizer purchase 2009 data was disaggregated by commercial and subsidized fertilizer purchases. Since I am interested in the profitability of fertilizer use in these countries within in the market network, without assistance, I do not include the subsidized fertilizer price observations in my fertilizer price district averages and only use commercial prices. Finally, since my data set includes three different countries with three different currencies and time periods, I convert all maize and fertilizer prices to real USD terms.

A value cost ratio is essentially a ratio of yield response to price ratio ((Maize yield/Nitrogen input) / (Price of nitrogen/Price of maize)). Although most literature supports that a VCR greater than 2 indicates that there are incentives for farmer to use fertilizer (Michael Morris, Valerie A. Kelly, Ron J. Kopicki, and Derek Byerlee 2007), I follow the threshold value of 2 for the AVCR but only 1 for the MVCR in accordance with economic theory, as discussed previously in section three.

[3] Province level average is used for districts that had less than 5 observations.

6.2 Marginal Physical Product (MPP) and Average Physical Product (APP)

I calculate the Marginal Physical Product (MPP) and the Average Physical Product (APP) of nitrogen at the admin 1 level and PN ratio group (Table 22). Table A5 shows the MPP of nitrogen for fields that harvested only, but for the remainder of this discussion I focus on the final weighted MPP of nitrogen, referred to as simply the MPP of nitrogen from here forward. For the Marginal Value Cost Ratio (MVCR) and the Average Value Cost Ratio (AVCR) calculation, I further disaggregate the MPP and APP by year.

The MPP of nitrogen is positive across all three PN ratio groups in all regions of all countries except in South Malawi (Table 21). In Kenya, MPP values range from 8.9 in Central Province for PN ratio group 1 (PN ratio 0 - .24) to 57.4 in Central Kenya for PN ratio group 3 (PN ratio 1 and higher). Interestingly the same Province has both the lowest and highest MPP values in the country. Generally the MPP of nitrogen is lowest for PN ratio group 1, and highest among PN ratio group 3.

In Zambia, the lowest MPP value is seen in Western Province in PN ratio group 1 at a value of 7.6. The highest MPP of nitrogen is also in Western Province but under the PN ratio group 2. MPP values are the lowest in PN group 1 and highest in group 2 for all Provinces.

MPP trends in Malawi are similar to those in Zambia. The MPP values in Malawi are lower for PN ratio group 1 than group 2 in every region. MPP values range from 9.9 in the South region for PN ratio group 1 to 18.2 in the North region for PN ratio group 2. One region, South, has cases in the PN ratio group 3. The MPP of nitrogen for those cases is negative but small in magnitude (-2.2).

These estimates provide a very helpful disaggregated range of maize response rates to nitrogen compared to other research that often estimates a single response rate at the national level. For example, average maize response rates to nitrogen across East and Southern Africa reported at 17 kg/ha by Yanggen et al (David Yanggen, Valerie Kelly, Thomas Reardon, and Anawar Naseem 1998).

Table 21. MPP of nitrogen by region and Phosphorus:Nitrogen ratio group			
	Phosphorus:Nitrogen Ratio		
	(1)	**(2)**	**(3)**
Admin 1	**0-.24**	**.25-.99**	**>=1**
Eastern Kenya	10.5	29.5	41.1
Nyanza Kenya	9.3	16.2	35.9
Western Kenya	11.4	15.1	28.6
Central Kenya	8.9	27.5	57.4
Rift valley Kenya	10.5	13.3	23.9
Central Zambia	10.7	15.5	
Copperbelt Zambia	10.6	21.5	
Eastern Zambia	10.7	20.8	
Luapula Zambia	10.3	24.6	
Lusaka Zambia	9.8	11.7	
Northern Zambia	10.3	14.8	
Nwestern Zambia	10.3	28.1	
Southern Zambia	10.6	21.5	
Western Zambia	7.6	28.3	
North Malawi	10.2	18.2	
Central Malawi	10.9	14.5	
South Malawi	9.9	16.6	-2.2

Turning to APP trends, in Kenya the APP of nitrogen value trends were more varied than the MPP trends (Table 22). APP values were the highest for the low PN ratio value group for nearly half of the provinces (Eastern, and Nyanza), while the other half of the provinces (Rift Valley, Central, and Western) had the highest APP values for the highest PN ratio group (over 1). APP values in Kenya ranged from 16.5 in the Rift Valley Province (for the lowest PN ratio group), to 76.9 in Nyanza Province (also for the lowest PN ratio group).

APP values in Zambia varied very little within each region across the PN ratio groups. However, there was a great deal of variation within the country across regions. APP values range from 10.7 in the middle PN ratio group in Lusaka Province to 205.5 in the highest PN ratio group in Western Province. APP values were nearly even across PN groups for most regions but were the highest for the lowest PN ratio group most often.

Compared to Kenya and Zambia, APP values were quite low and did not vary as much in Malawi, ranging from 8.6 in the middle PN ratio group in the Central region to 20.6 in the highest PN ratio group in the North region. APP trends between PN ratio groups also varied across the country, with the highest APP values in the highest PN ratio group for the Central and North regions, while the South region has the highest APP values in the middle PN ratio group. While APP values are quite even across PN ratio groups in South and Central, there is a gap in North region between low APP values in PN ratio groups 1 and 2 and almost twice as high APP value in PN ratio group 3.

Table 22. APP of nitrogen by region and Phosphorus:Nitrogen ratio group

	Phosphorus:Nitrogen Ratio		
	(1)	**(2)**	**(3)**
Admin 1	**0-.24**	**.25-.99**	**>=1**
Eastern Kenya	64.5	61.0	59.5
Nyanza Kenya	76.9	58.0	68.7
Western Kenya	29.8	28.6	29.9
Central Kenya	26.1	25.9	32.6
Rift valley Kenya	16.5	18.8	20.8
Central Zambia	16.6	16.1	16.5
Copperbelt Zambia	17.6	11.9	16.9
Eastern Zambia	27.1	27.7	26.9
Luapula Zambia	23.8	21.7	23.2
Lusaka Zambia	10.9	10.7	10.9
Northern Zambia	22.1	20.5	22.0
Nwestern Zambia	31.5	31.9	31.1
Southern Zambia	23.7	23.3	23.9
Western Zambia	192.3	183.5	205.5
North Malawi	9.8	9.9	20.6
Central Malawi	9.0	8.6	9.6
South Malawi	15.3	16.3	14.9

6.3 Price Ratio – price of input to price of output (Pn/Po)

Price ratios (price of nitrogen to price of maize) generally increased over time, with only a slight decrease in Kenya between 2006 and 2009 (Table 23). Increases in the price ratio over time were small and gradual in Kenya, and more noticeable in Zambia and Malawi. The highest national average price ratio is seen in Malawi in 2009 (15.1). Looking at the one year each country had a panel, 2003, the price ratio at the national level is highest in Kenya (10.8), followed by Zambia (10.5), and Malawi with the lowest price ratio (7.7).

There exists variation of price ratio trends over time within the three countries as well. The gap in the price ratio range within the country in Malawi increased over time: price ratios were similar across all three regions of the country in 2003 but had spread considerably by 2009 as price ratios in the North and Central regions increased more than those in the South region. Between 2003 and 2009, the price ratio in the North region increased the most, and increased the least in the South region. In Zambia, although the price ratios increased over time, the price ratio gap between regions stayed generally the same over time. The price ratio increased the most over time in Northern and Luapula Provinces, and the least in Southern Province. Central province had one of the highest price ratios in both years. The range of price ratios in Kenya also stayed fairly constant over time as price ratios increased in all provinces. Eastern Province consistently had the highest price ratio in all years.

Compared with findings from other research, the price ratios in my sample are on the higher end. Based on CIMMYT World Maize Facts and Trends, the median nitrogen-maize price ratio in Kenya from 1980 -95 was 7.3, for Malawi it dropped from 10.7 between 1977 – 1987 to 7.7 between 1988 – 1994, and were even lower for Zambia at 3.3 from 1971 – 1989 and 5.4 from

1990 to 19994 (Wilfred Mwangi 1996). The discrepancy is certainly at least partially due to the difference in time periods, and may also simply reflect survey data versus secondary data rates.

Table 23. Average Nitrogen Maize Price Ratio by region within country and year

	Year					
Admin 1	**1999**	**2003**	**2004**	**2006**	**2007**	**2009**
Kenya national	**10.7**	**10.8**		**13.9**		**12.49**
Eastern Kenya	11.6	12.5		15.3		15.7
Nyanza Kenya	10.4	10.3		14.7		12.2
Western Kenya	10.2	9.8		12.8		11.9
Central Kenya	8.7	8.8		11.8		12.7
Rift valley Kenya	11.2	11.5		14.4		11.9
Zambia national		**10.5**			**14.4**	
Central Zambia		14.9			18.4	
Copperbelt Zambia		8.7			18.6	
Eastern Zambia		11.4			14.1	
Luapula Zambia		5.6			12.4	
Lusaka Zambia		7.0			9.2	
Northern Zambia		4.7			10.6	
Nwestern Zambia		7.7			9.4	
Southern Zambia		14.3			17.8	
Western Zambia		5.5			9.0	
Malawi National		**7.7**	**9.6**		**14.7**	**15.1**
North Malawi		8.9	11.4		11.3	23.6
Central Malawi		7.9	9.7		14.1	16.5
South Malawi		7.1	8.8		16.5	11.9

6.4 MVCR and AVCR Results

I calculate MVCRs and AVCRs by admin 1, year (Tables 24 and 26), and PN ratio group levels (Tables 25 and 27). Looking at average MVCRs for nitrogen to maize by admin 1, Kenya has by far the highest percent of fields where MVCR>1 at the national level. As expected, Zambia is second, and Malawi is last with very few cases with MVCR>1. The proportion of households that have an MVCR above 2 in Kenya greatly declined over the time period of the panel, from 60% of cases in 1999 to only 26% of cases in 2009. The same trend is true in Zambia and Malawi, with nearly 0 percent of fields in Zambia and 0 percent of fields in Malawi by the end of the respective survey periods with an MVCR above 2. At the sub-national levels, Nyanza Province in Kenya, Northern Province in Zambia, and South region in Malawi have the highest rates of MVCR > 1 within each of the respective countries.

In Zambia, the high proportion of cases with MVCR values above 2 in Western Province, relative to other Provinces, is surprising. Often referred to in literature as a Province with little agro-climatological potential, the MVCR findings suggest that there is room for expanded nitrogen application in the province with economic benefits, and agricultural growth, for the producers.

Table 24. Percent of fields with MVCR greater than 1.0 and greater than 2.0 by region within country and year

Country	Level	MVCR	1999	2003	2004	2006	2007	2009
Kenya	**National**	**Above 1**	**94.5**	**96.7**		**72.30**		**96.5**
		Above 2	**61.2**	**16.3**		**24.75**		**26.2**
	Eastern	Above 1	70.6	95.9		96.30		97.8
		Above 2	64.7	67.4		51.85		44.4
	Nyanza	Above 1	98.0	95.8		98.28		100.0
		Above 2	84.0	52.8		68.97		53.5
	Western	Above 1	100.0	100.0		93.15		96.6
		Above 2	50.5	0.0		25.34		22.2
	Central	Above 1	58.8	60.0		71.43		68.8
		Above 2	58.8	60.0		71.43		31.3
	Rift valley	Above 1	99.3	95.2		40.49		97.7
		Above 2	60.0	0.0		0.0		10.8
Zambia	**National**	**Above 1**		**61.4**			**46.7**	
		Above 2		**18.5**			**1.8**	
	Central	Above 1		28.6			30.7	
		Above 2		12.5			0.0	
	Copperbelt	Above 1		84.3			37.1	
		Above 2		36.3			7.8	
	Eastern	Above 1		60.9			69.8	
		Above 2		5.3			1.2	
	Luapula	Above 1		100.0			0.0	
		Above 2		38.9			0.0	
	Lusaka	Above 1		100.0			46.4	
		Above 2		0.0			0.0	
	Northern	Above 1		100.0			71.2	
		Above 2		72.1			0.0	

	Table 24 (cont'd)							
	Nwestern	Above 1		100.0			70.5	
		Above 2		5.6			6.8	
	Southern	Above 1		28.1			15.1	
		Above 2		0.0			0.0	
	Western	Above 1		56.3			12.5	
		Above 2		43.8			12.5	
Malawi	**National**	**Above 1**		**89.6**	**76.4**		**30.9**	**10.8**
		Above 2		**16.0**	**4.2**		**2.2**	**0.0**
	North	Above 1		34.4	64.2		34.5	9.9
		Above 2		0.0	4.5		4.9	0.0
	Central	Above 1		100.0	68.3		24.4	10.9
		Above 2		23.2	0.0		0.0	0.0
	South	Above 1		99.2	84.8		31.7	11.0
		Above 2		16.9	5.7		1.8	0.0

When stratified by PN ratio groups, PN ratio group 3 with the highest PN ratio values (greater than 1) have the greatest proportion of MVCRs above 1 in Kenya and Malawi, followed closely by PN ratio group 2 (Table 25). However, trends are mixed for MVCR values above 2; in Kenya and Zambia the proportion of cases with MVCR's above 2 declines with PN ratio group with very low proportions for the two lower PN ratio groups, while in Malawi there are no cases with a MVCR above 2 by the final year of the survey (2009).

Table 25. Percent of fields with MVCR greater than 1.0 and greater than 2.0 by Phosphorus:Nitrogen ratio group within country and year

Country	PN Ratio	MVCR	1999	2003	2004	2006	2007	2009
Kenya	**0 - .24**	Above 1	50.0	60.6		9.4		59.3
		Above 2	0.0	0.0		0.0		0.0
	.25 - .99	Above 1	100.0	99.1		61.9		99.0
		Above 2	16.7	12.9		5.4		6.8
	>=1	Above 1	100.0	100.0		100.0		100.0
		Above 2	100.0	23.1		57.4		61.2
Zambia	**0 - .24**	Above 1		59.9			45.2	
		Above 2		16.1			1.0	
	.25 - .99	Above 1		83.0			76.7	
		Above 2		54.7			16.3	
	>=1	Above 1						
		Above 2						
Malawi	**0 - .24**	Above 1		88.9	74.6		21.8	1.8

		Table 25 (cont'd)						
		Above 2		9.5	0.8		0.0	0.0
	.25 - .99	Above 1		100.0	100.0		74.5	91.7
		Above 2		72.7	43.48		12.8	0.0
	>=1	Above 1		0.0	0.0		0.0	100.0
		Above 2		0.0	0.0		0.0	0.0

AVCR values at the national level follow similar trends compared to the MVCR values (Table 26). Kenya again has the highest percent of households with an AVCR above 2, which is deemed as "profitable" in literature, followed by Zambia, and then Malawi. The proportion of cases with an AVCR above 2 at the national level declined over time in Kenya and Malawi, but not in Zambia, a very important result.

Table 26. Percent of fields with AVCR greater than 1.0 and greater than 2.0 by region within country and year

Country	Level	AVCR	1999	2003	2004	2006	2007	2009
Kenya	**National**	**Above 1**	**100.0**	**67.04**		**63.2**		**100.0**
		Above 2	**96.2**	**67.04**		**63.2**		**78.6**
	Eastern	Above 1	100.0	100.0		100.0		100.0
		Above 2	100.0	100.0		100.0		87.3
	Nyanza	Above 1	100.0	100.0		100.0		100.0
		Above 2	100.0	100.0		100.0		100.0
	Western	Above 1	100.0	100.0		100.0		100.0
		Above 2	100.0	100.0		100.0		100.0
	Central	Above 1	100.0	100.0		100.0		100.0
		Above 2	0.0	100.0		100.0		0.0
	Rift valley	Above 1	100.0	0.0		0.0		100.0
		Above 2	100.0	0.0		0.0		62.9
Zambia	**National**	**Above 1**		**86.1**			**91.7**	
		Above 2		**53.7**			**59.3**	
	Central	Above 1		50.9			50.9	
		Above 2		28.2			16.8	
	Copperbelt	Above 1		42.3			81.6	
		Above 2		21.4			68.2	
	Eastern	Above 1		100.0			100.0	
		Above 2		58.9			75.5	
	Luapula	Above 1		100.0			100.0	
		Above 2		100.0			89.74	
	Lusaka	Above 1		100.0			100.0	
		Above 2		0.0			0.0	
	Northern	Above 1		100.0			100.0	

Table 26 (cont'd)

		Above 2		100.0			82.9	
	Nwestern	Above 1		100.0			100.0	
		Above 2		100.0			100.0	
	Southern	Above 1		86.4			100.0	
		Above 2		20.8			18.4	
	Western	Above 1		100.0			100.0	
		Above 2		100.0			100.0	
Malawi	**National**	**Above 1**		**86.0**	**80.5**		**52.5**	**59.4**
		Above 2		**25.9**	**12.1**		**9.1**	**0.0**
	North	Above 1		100.0	46.4		6.7	0.0
		Above 2		22.4	2.7		0.0	0.0
	Central	Above 1		44.7	72.8		0.0	49.4
		Above 2		15.3	0.0		0.0	0.0
	South	Above 1		100.0	100.0		93.2	81.5
		Above 2		32.1	21.4		16.7	0.0

I then look at the AVCR values in each country stratified by PN ratio groups (Table 27). Interestingly, PN ratio group 2 (PN ratio of .25 -.99) has the highest proportion of fields with AVCR above 1 and 2. More specifically, AVCR values are generally the highest in each country among cases that fall in the middle PN ratio group (PN ratio of .25 -.99), followed by the lowest PN ratio group (PN ratio of 0 - .24), and AVCR values are the lowest for highest PN ratio group (PN ratio of 1 or above). In Kenya, there is a slight dip in proportions of cases with AVCR's above 1 and 2 from 1999 to 2003 and 2006 but then recover in 2009. For Zambia, although PN ratio group 1 (lowest PN ratio) was the dominant group in 2003, by 2007 the proportion of fields with an AVCR over 1 and 2 is more even across PN ratio groups. The percent of fields with an AVCR value of 1 or 2 diminished greatly over time in Malawi across all PN ratio groups. The highest PN ratio group has the smallest percent of cases above 1 and no cases with a AVCR above 2 in any year, while the middle and lowest PN ratio groups have closer proportions of cases but also diminish to no cases with an AVCR above 2 by 2009.

Table 27. Percent of fields with AVCR greater than 1.0 and greater than 2.0 by Phosphorus:Nitrogen ratio group within country and year								
Country	**PN Ratio**	**AVCR**	**1999**	**2003**	**2004**	**2006**	**2007**	**2009**
Kenya	**0 - .24**	Above 1	100.0	75.8		59.4		100.0
		Above 2	81.6	75.8		59.4		74.1
	.25 - .99	Above 1	100.0	66.2		61.9		100.0
		Above 2	94.7	66.2		61.9		86.3
	>=1	Above 1	100.0	57.4		57.4		100.0
		Above 2	97.9	57.4		57.4		63.4
Zambia	**0 - .24**	Above 1		82.1			85.9	
		Above 2		52.4			54.4	
	.25 - .99	Above 1		77.4			88.6	
		Above 2		43.4			61.4	
	>=1	Above 1		77.8			88.9	
		Above 2		55.6			55.6	
Malawi	**0 - .24**	Above 1		85.7	83.3		50.7	58.9
		Above 2		23.8	14.4		11.2	0.0
	.25 - .99	Above 1		86.5	47.8		59.6	63.9
		Above 2		4.6	0.0		10.6	0.0
	>=1	Above 1		100.0	66.7		33.3	33.3
		Above 2		0.0	0.0		0.0	0.0

Chapter 7: Conclusions

This research focused on profitability of fertilizer use on maize in Kenya, Zambia, and Malawi. In Chapter 4, important characteristics of my sample were analyzed. Chapter 5 examined the results of the maize yield response model, and Chapter 6 investigated the main focus of this paper: differences in profitability of fertilizer use across and within each country.

Chapter 4 explored important attributes of the fields in my pooled, cross-country, unbalanced sample of panel maize fields in Kenya, Zambia, and Malawi. First, fertilizer application (excluding non-users) and use rates on maize fields were assessed across and within countries. On average at the national level, the fertilizer application rate (kg/ha) in Zambia is by far the highest, while rates in Kenya and Malawi are very similar. In contrast, the percent of farmers using fertilizer (fertilizer use rates) are the lowest in Zambia of the three countries (around 40%), and Kenya and Malawi again have similar rates (around 75 – 85 %). This indicates high access (and use) of fertilizer among a more concentrated group in Zambia, whereas in Malawi and Kenya more farmers are using fertilizer on maize fields but much smaller quantities. Secondly, Kenya has a much higher national rate of hybrid seed use, almost doubling use rates in Zambia and Malawi. Thirdly, monocropped planting scheme for maize fields was much more prevalent in Zambia than in Kenya or Malawi. Finally, Zambia and Malawi both have a similar patterns of the phosphorus to nitrogen ratio content of fertilizers applied with the large majority falling in the <.25 range, which is in contrast to most fertilizer applied in Kenya with a higher phosphorus to nitrogen ratio (>.25). These trends are in line with expectations given the popularity of DAP in Kenya that has a high phosphorus content, and fertilizers with high nitrogen content (such as Urea) in Zambia and Malawi.

In Chapter 5, a maize yield response function was used to investigate the effects of various factors on maize yield. The correlated random effects with the mundlak-chamberlain device was used to estimate the model in order to control for expected correlation between the unobserved explanatory variables (such as farm managerial skill) and the observed measures and other variables (such as nitrogen use) and allow for estimation of time invariant variables (such as soil quality). Results of the production function estimation produced both evidence for some commonly cited trends and raised questions about other trends for further research. As expected, lower quality of nutrient levels in soil have a negative effect on maize yield, hybrid seed use and household assets have a positive effect, and field size has a negative and increasing relationship with maize yield. An interesting finding that would be an important topic for further research is the strong significance of the regional dummies for each country. It would be useful to further investigate the spatial variation that differentiates maize response between these areas. The model was also estimated after stratifying the sample by phosphorus to nitrogen ratio (PN ratio) of fertilizer applied, providing important and unique contribution to the field of research on this topic. Some important findings of the stratified estimation is that hybrid seed use was only significant for the middle PN ratio value (.25 - .99) indicating best results in maize yield from using hybrid seeds when applying fertilizer with a phosphorus to nitrogen ratio between .25 and .99. One potential limitation of the regression results is that the soil variables used may not be capturing the intended underlying concept. This may be due to the aggregated attributes that they represent.

Finally, in Chapter 6 the main focus of the paper, profitability of fertilizer use on maize, is examined. This work is completed in stages, first calculating and analyzing both the average and marginal physical products (APP and MPP) of nitrogen to indicate maize response to nitrogen, followed by the nitrogen to maize price ratios (PR) to reflect nitrogen and maize price relationships, and finally the average and marginal value cost ratio (AVCR and MVCR) to indicate profitability of fertilizer use. The main hypothesis of this paper was that price ratios would be the limiting factor in the profitability of fertilizer use on maize, while the physical products of nitrogen would be adequate.

Based on market structure, infrastructure, and policies implemented in each of the countries, it was hypothesized that the nitrogen maize price ratios (PR) will generally be low enough (below 2) to indicate adequate economic incentive, in Kenya but not in Zambia and Malawi. However, my findings indicate that the price ratio is too high in Zambia, Malawi, and Kenya as well. Although Kenya has the lowest price ratios of the three countries based on the most recent year of data for each, price ratios are still quite high in Kenya. Price ratios also increased over time in each country, indicating that fertilizer prices are increasing relative to maize, instead of the opposite desired trend. This confirms the main hypothesis that price ratios would be the limiting factor in fertilizer use profitability, while maize response to nitrogen would be sufficient.

Finally, I hypothesized that fertilizer use would be profitable for most farmers in all three countries but with little to no room for expanded profitable use in Kenya, and moderate room for expanded profitable use in Zambia and Malawi. My AVCR findings confirm that fertilizer use is profitable for most farmers in Kenya (80% of cases in 2009) and Zambia (60% in 2007), but not in Malawi (0% of cases in 2009). The proportion of farms with an AVCR greater than 1 (indicating profitable use of fertilizer) is the lowest in the North region. Furthermore, the MVCR results show that the room for expanded fertilizer use (MVCR greater than 1) in Malawi is lower than hypothesized and has declined significantly over time across the country. The findings for

Kenya were surprising showing a very high proportion of farms that could expand fertilizer use, and only a slightly higher than expected proportion in Zambia. These results indicate that prevalence of profitable fertilizer use and room for expanded use is the highest (on average) in Kenya, followed by Zambia, and lastly Malawi.

These finding have important implications for areas of investment for governments (market development) in regards to boosting maize productivity, and two, practices for farmers and extension services regarding fertilizer application. My findings seem to reflect patterns of investment in market and agricultural development by each of the countries. The highest levels of profitable fertilizer use and room for expanded use are found in Kenya where the government implemented strong market development policies and invested in agricultural research and services. This highlights the importance of investment in the agricultural sector in initiatives such as extensions services and market enhancement for both inputs and outputs. Further research on the various structural differences between these countries and the exact role they play in these outcomes would be very useful.

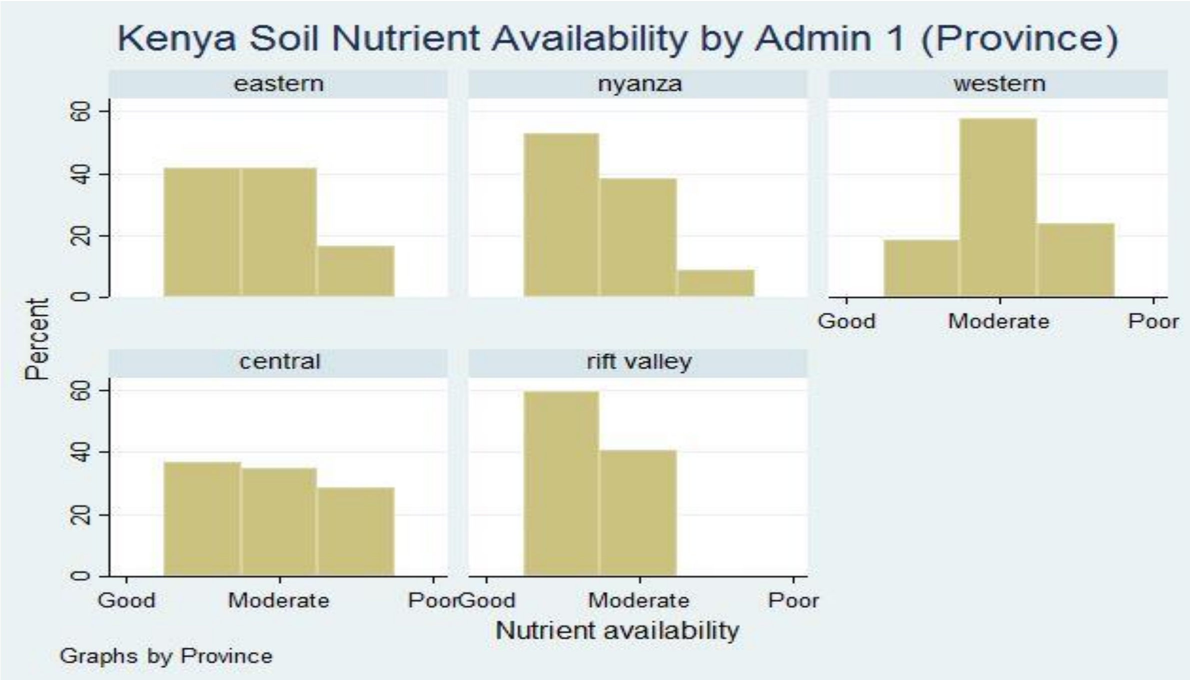
APPENDIX

Table A 1. Fertilizer Nitrogen Conversion Calculations

Fertilizer type	Kgs N conversion factor	Kgs P conversion factor
DAP	.18	.2006
MAP	.11	.2267
TSP	0	.2006
SSP	0	.0959
NPK (20:20:0)	.2	.0872
NPK (17:17:0)	.17	.0741
NPK (25:5:5S)	.25	.0281
CAN (26:0:0)	.26	0
ASN (26:0:0)	.26	0
UREA (46:0:0)	.46	0
SA (21:0:0)	.21	0
Manure	0	0
foliar feed	.12	.0436
NPK (23:23:23)	.23	.1003
NPK (20:10:10)	.2	.0436
DAP + CAN	(.18+.26)/2	.2006
DSP	0	.0847
NPK (23:23:0)	.23	.1003
NPK (17:17:17)	.17	.0741
NPK (18:14:12)	.18	.061
NPK (15:15:15)	.15	.0654
Mavuno - basal	.1	.1134
Mavuno - top dressing	.3	.0349
NPK+CAN	(.22+.26)/2	(.0262)/2
NPK (22:6:12) TE	.22	.0262
NPK (26:5:5)	.26	.0218
NPK (22:11:11)	.22	.048
mavuno top dress + urea	(.3+.46)/2	(.0348)/2
Cmpd D (10:20:10)	.1	.0872
Cmpd X (20:10:5)	.2	.0436
CMPD S (8:21)	.08	.09156
TSP	0	.1918
SSP	0	.0828
Cmpd R (20:20:0)	.2	.0872
Urea	.46	0
Ammonium Nitrate: (34:0)	.34	0
CAN (26:0)	.26	0
Chitowe (23:21:0)	.23	.0916

Table A1. (cont'd)		
"Mixture": 1st fertilizer coded as 2/3 23-21-0 & 1/3 urea, 2nd fertilizer coded as: 1/2 CAN & 1/2 urea	(.23*fkgs*.667)+(.46*fkgs*.333)	(.0*fkgs*.5)+(.0*fkgs*.5)

Figure A 1. Soil Nutrient Availability by Admin 1 within Country



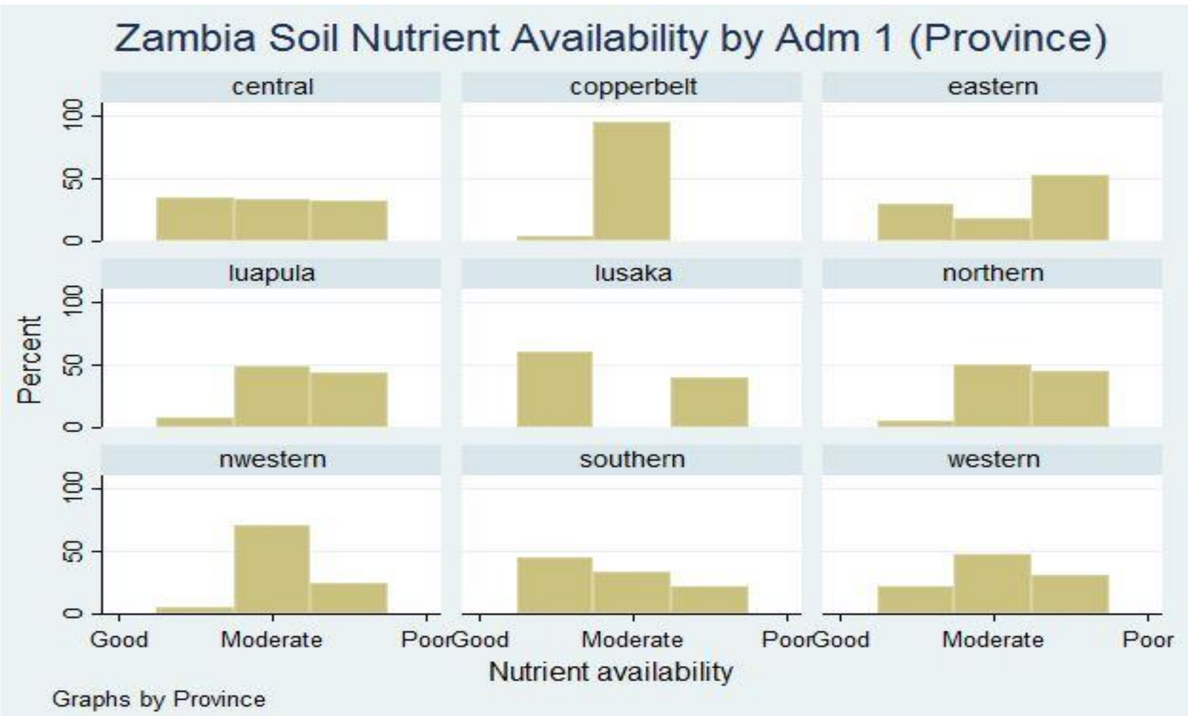


Figure A1. (cont'd)

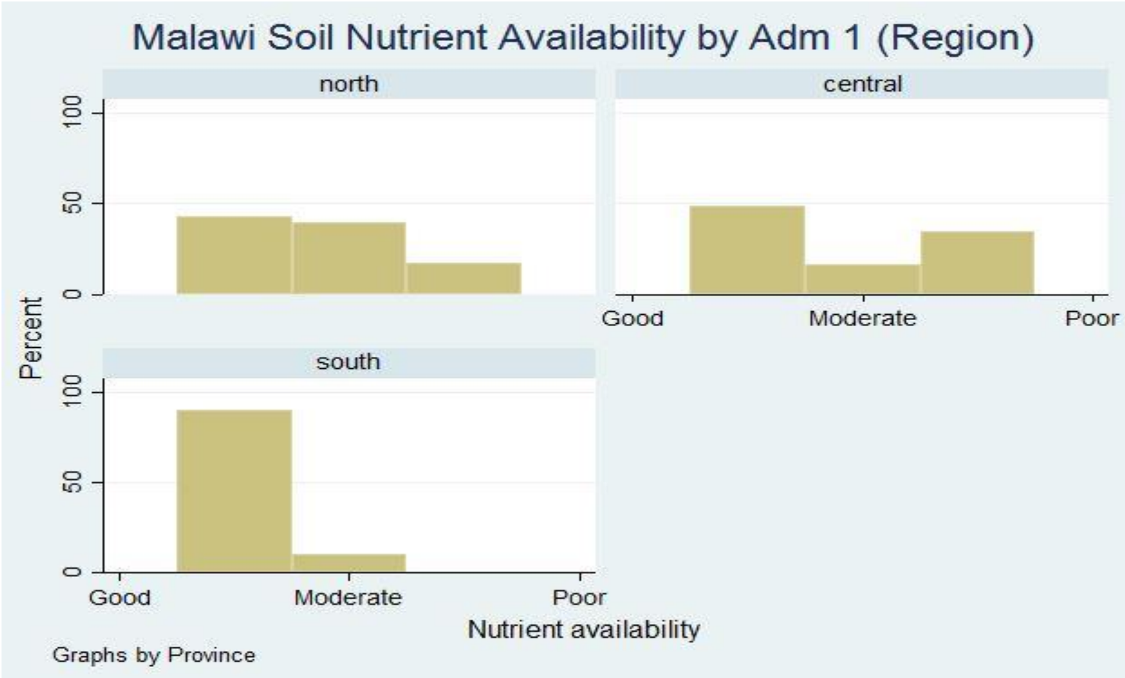


Figure A 2. Soil Nutrient Retention Capacity by Admin 1 within Country

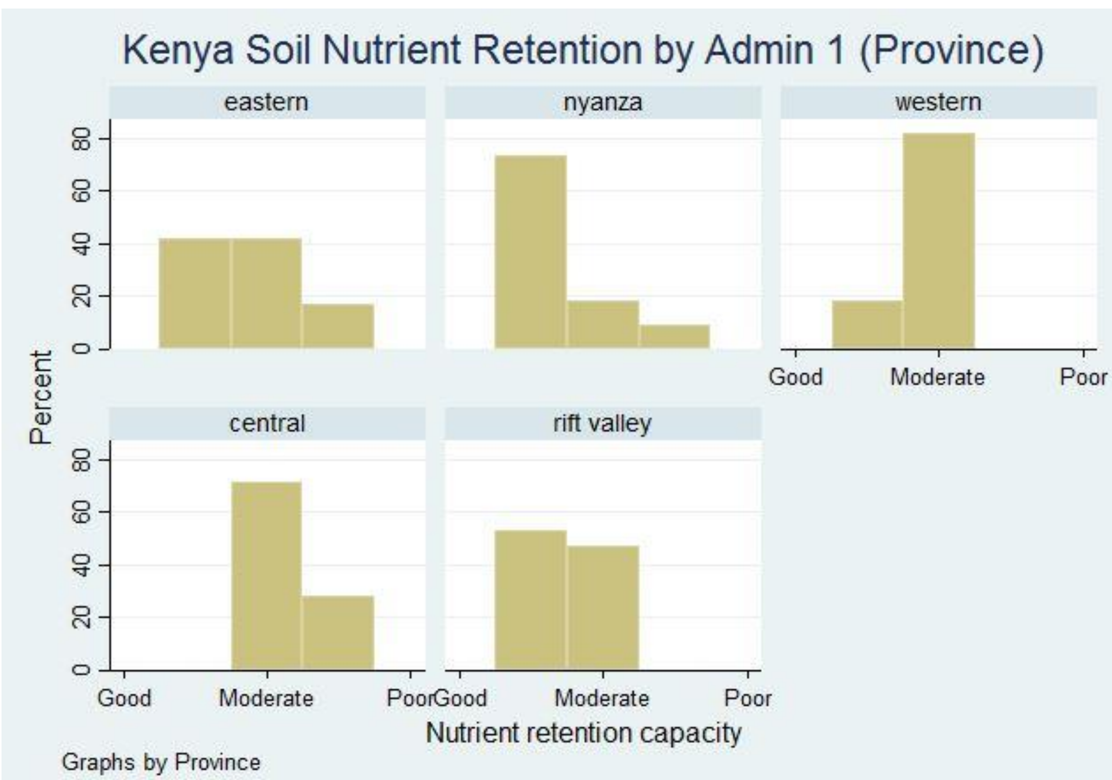


Figure A2. (cont'd)

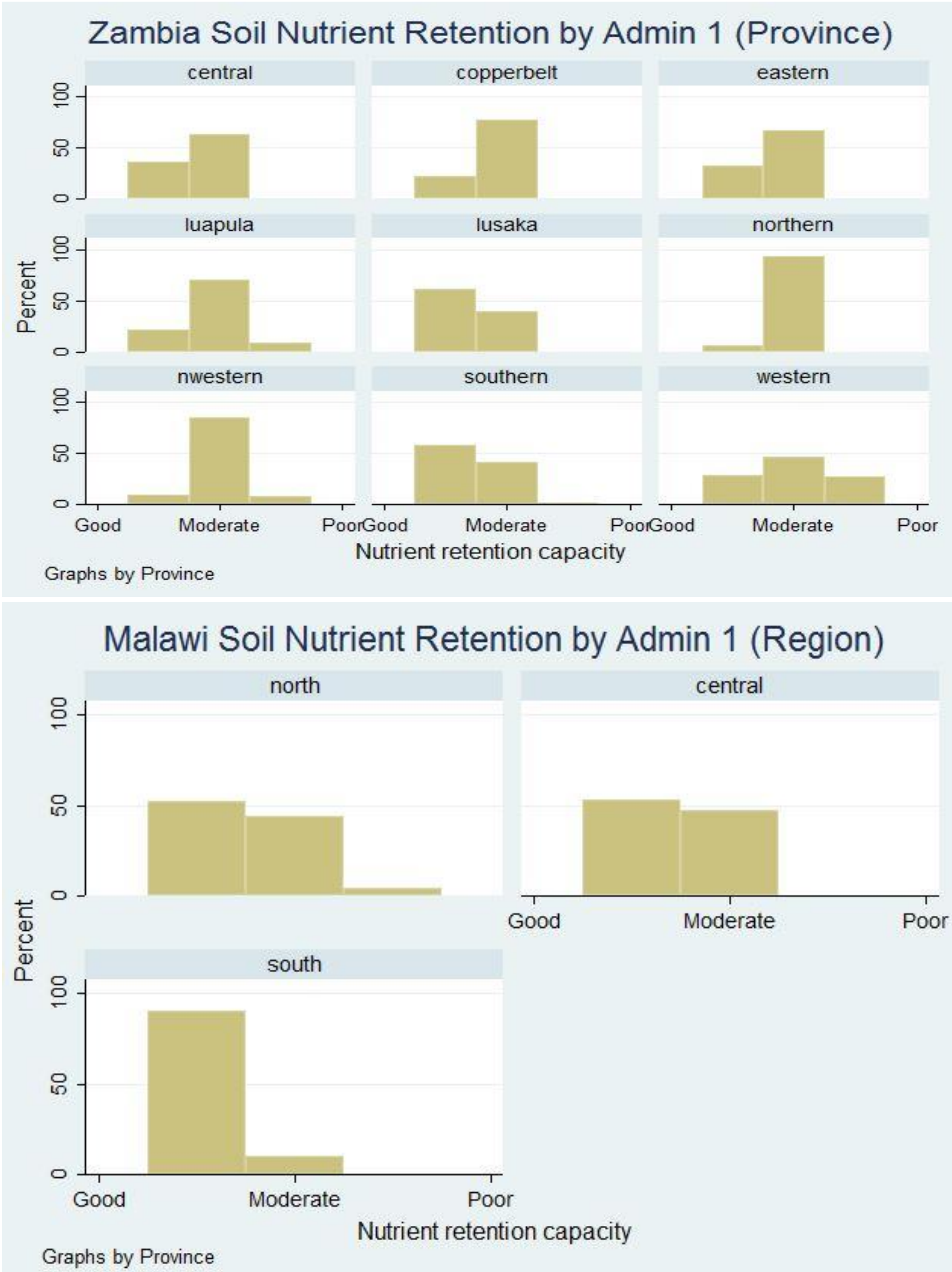


Table A 2. Standard deviation of variables used in production, total and by PN ratio group

	Total sample N = 8,674			PN ratio Gp 1 (0 - .24 PN) N = 3,052			PN ratio Gp 2 (.25 - .99) N = 1,035			PN ratio Gp 3 (>=1) N = 677		
	Overall	Between	Within	Overall	Between	Within	Overall	Between	Within	Overall	Between	Within
Maize yield	1160.7	894.9	725.1	1201.8	1067.3	622.4.4	1398.7	1215.9	689.5	11.6	1041.4	666.6
Nitrogen	40.6	34.3	22.8	45.0	38.7	23.8	26.7	24.9	11.7	8.2	7.6	4.3
Mod soil nutrs	.5	.5	0	.5	.5	0	.5	.5	0	.5	.5	0
Poor soil nutrs	.4	.4	0	.5	.5	0	.4	.4	0	.3	.3	0
Moderate soil nutr retention	.5	.5	0	.5	.5	0	.5	.5	0	.5	.5	0
Poor soil nutr retention	.2	.2	0	.1	.1	0	.2	.2	0	.2	.2	0
Rainfall	355,1	304.1	169.4	326.9	287.6	175.7	371.3	396.1	99.7	251.8	239.1	108.8
Hybrid seeds	.5	.4	.3	.5	.4	.2	.4	.4	.1	.3	.3	.1
Field size	.7	.6	.4	.8	.7	.3	.7	.6	.3	.5	.5	.2
Household Assets	3.6	3.0	1.6	2.1	2.1	.6	5.5	4.7	2.0	7.0	6.6	2.7
Monocropped	.5	.4	.2	.5	.4	.2	.4	.4	.1	.2	.1	.1

Table A 3. Total Sample Correlation

	MZyiel	kgsN ha	kgsP ha	Mod soil nut	Poor soil nut	Mod soil nut ret	Poor soil nut ret	hybuse	hect	rain	mono
MZyield kgha	1										
kgsN ha	0.35	1									
kgsP ha	0.43	0.67	1								
Mod soil nut	0.07	-0.01	0.05	1							
Poor soil nut	0.01	0.08	-0.03	-0.42	1						
Mod soil nut ret	0.11	0.08	0.08	0.49	0.40	1					
Poor soil nut ret	-0.02	-0.07	-0.05	-0.13	0.31	-0.18	1				
hybuse	0.26	0.29	0.41	0.01	-0.11	-0.07	-0.01	1			
hect	0.05	0.01	-0.01	-0.03	0.04	0.03	-0.07	0.12	1		
rain	-0.08	0.17	-0.11	-0.06	0.07	0.04	-0.09	-0.15	0.03	1	
mono	-0.01	0.01	-0.29	-0.01	0.24	0.16	0.00	-0.19	0.18	0.27	1
(obs=8674)											

Table A 4. Kenya Correlations											
	MZyiel	kgsN ha	kgsP ha	Mod soil nut	Poor soil nut	Mod soil nut ret	Poor soil nut ret	hybuse	hect	rain	mono
MZyield kgha	1										
kgsN ha	0.44	1									
kgsP ha	0.42	0.74	1								
Mod soil nut	0.034	0.03	-0.01	1							
Poor soil nut	-0.07	-0.02	-0.05	-0.33	1						
Mod soil nut ret	0.13	0.18	0.14	0.68	0.07	1					
Poor soil nut ret	-0.07	-0.11	-0.13	-0.20	0.60	-0.22	1				
hybuse	0.36	0.37	0.46	-0.05	-0.07	0.06	-0.09	1			
hect	0.17	0.18	0.16	-0.06	-0.15	-0.08	-0.13	0.16	1		
rain	0.28	0.27	0.33	0.08	-0.16	0.16	-0.12	0.28	0.22	1	
mono	0.07	-0.02	-0.03	-0.02	-0.04	-0.03	-0.02	-0.01	0.05	0.00	1
(obs=2149)											

Table A 5. Zambia Correlations											
	MZyiel	kgsN ha	kgsP ha	Mod soil nut	Poor soil nut	Mod soil nut ret	Poor soil nut ret	hybuse	hect	rain	mono
MZyield kgha	1										
kgsN ha	0.42	1									
kgsP ha	0.41	0.94	1								
Mod soil nut	-0.00	-0.00	0.00	1							
Poor soil nut	0.03	0.12	0.11	-0.58	1						
Mod soil nut ret	0.03	0.12	0.11	0.33	0.42	1					
Poor soil nut ret	-0.04	-0.05	-0.05	-0.14	0.24	-0.24	1				
hybuse	0.2	0.38	0.36	0.02	-0.08	-0.09	-0.02	1			
hect	0.00	0.02	0.02	-0.06	-0.00	-0.03	-0.06	0.21	1		
rain	0.08	0.15	0.14	0.13	0.09	0.28	-0.13	-0.16	-0.07	1	
mono	0.09	0.04	0.03	-0.11	0.06	-0.06	0.00	0.036	0.01	0.019	1
(obs=4616)											

Table A 6. Malawi Correlations											
	MZyiel	kgsN ha	kgsP ha	Mod soil nut	Poor soil nut	Mod soil nut ret	Poor soil nut ret	hybuse	hect	rain	mono
MZyield kgha	1										
kgsN ha	0.42	1									
kgsP ha	0.37	0.75	1								
Mod soil nut	0.03	0.05	0.08	1							
Poor soil nut	-0.02	0.03	0.06	-0.17	1						
Mod soil nut ret	-0.00	0.04	0.08	0.62	0.54	1					
Poor soil nut ret	-0.01	0.00	0.01	-0.05	0.27	-0.05	1				
hybuse	0.10	0.15	0.14	-0.03	0.07	0.01	0.07	1			
hect	-0.19	-0.17	-0.16	0.01	0.05	0.03	-0.02	0.07	1		
rain	0.00	0.09	0.07	-0.15	0.03	-0.14	0.17	0.02	0.02	1	
mono	0.03	0.06	0.07	0.10	0.05	0.07	0.11	0.10	-0.06	0.05	1
(obs=1909)											

Table A 7. OLS, CRE, FE Regression Results

VARIABLES	OLS	CRE	FE
kgs Nitrogen used per ha	12.40***	10.31***	10.31***
	(1.693)	(2.422)	(2.418)
kgsN^2	-0.0160**	-0.0111	-0.0111
	(0.0111)	(0.0141)	(0.0133)
tot rainfall, plant+grow mths(mm)	0.108**	-0.0526	-0.0526
	(0.0471)	(0.0643)	(0.0611)
kgN*total rainfall	-0.00295***	-0.00298**	-0.00298**
	(0.000994)	(0.00137)	(0.00131)
used hybrid seeds on field y/n	193.9***	125.9***	125.9***
	(28.04)	(41.02)	(40.10)
kgN*hybrid use	1.804**	1.562	1.562
	(0.716)	(0.950)	(0.951)
field ha	-334.1***	-650.2***	-650.2***
	(44.87)	(67.72)	(63.35)
field ha^2	74.59***	111.2***	111.2***
	(12.86)	(19.15)	(16.61)
tot hh assets	67.64***	43.72***	43.72***
	(8.827)	(16.40)	(14.77)
tot hh assets^2	-1.610***	-0.558	-0.558
	(0.278)	(0.448)	(0.414)
monocropped	113.6***	-13.38	-13.38
	(36.15)	(49.74)	(47.21)
Soil variable Dummies			
Good soil nutrient level	Omitted	Omitted	Omitted
Mod soil nutrient level	-133.2**	-135.6**	
	(55.77)	(57.67)	
Poor soil nutrient level	-198.0***	-181.6**	
	(67.01)	(71.03)	
Good soil nutrient hold cap	Omitted	Omitted	Omitted
Mod soil nutrient hold cap	76.10	79.05	
	(56.53)	(58.49)	
Poor soil nutrient hold cap	215.5**	187.7**	
	(84.33)	(87.54)	
Nitrogen*Soil dummy Interactions			
kgN*mod soil nutrient lvl	0.815	-2.328	-2.328
	(2.729)	(5.361)	(5.613)
kgN*poor soil nutrient lvl	-4.175	-1.874	-1.874
	(3.294)	(6.061)	(6.344)
kgN*mod soil nutr hold cap	3.172	3.450	3.450
	(2.729)	(5.410)	(5.663)

Table A7. (cont'd)			
kgN*poor soil nutr hold cap	9.764*	8.242	8.242
	(5.366)	(10.46)	(10.54)
kgN^2*mod soil nutrient	-0.00505	0.000615	0.000615
	(0.0187)	(0.0307)	(0.0332)
kgN^2*poor soil nutrient	0.0238	-0.0184	-0.0184
	(0.0238)	(0.0369)	(0.0396)
kgN^2*mod soil nutr hold cap	-0.00296	0.0192	0.0192
	(0.0184)	(0.0306)	(0.0332)
kgN^2*poor soil nutr hold cap	-0.0585*	-0.0131	-0.0131
	(0.0319)	(0.0590)	(0.0621)
Admin 1 Dummies			
RiftValley_Ken	Omitted	Omitted	Omitted
Eastern_Ken	-607.2***	-444.7***	
	(92.47)	(98.83)	
Nyanza_Ken	-872.7***	-720.9***	
	(67.75)	(72.24)	
Western_Ken	-337.1***	-267.1***	
	(69.88)	(71.22)	
Central_Ken	-915.3***	-759.7***	
	(133.7)	(136.1)	
Central_Zam	-695.8***	-867.7***	
	(80.26)	(87.88)	
Cpperbelt_Zam	-590.3***	-804.8***	
	(89.91)	(99.65)	
Eastern_Zam	-511.2***	-664.7***	
	(76.29)	(86.53)	
Luapula_Zam	-394.3***	-544.9***	
	(128.3)	(132.6)	
Lusaka_Zam	-845.0***	-966.5***	
	(108.7)	(113.8)	
Northern_Zam	-597.3***	-730.8***	
	(84.23)	(91.69)	
NWestern_Zam	-745.8***	-864.3***	
	(86.83)	(94.44)	
Southern_Zam	-594.7***	-691.1***	
	(79.93)	(86.09)	
Western_Zam	-955.0***	-971.8***	
	(78.08)	(83.85)	
North_Mal	-1,382***	-1,470***	
	(71.52)	(75.59)	
Central_Mal	-1,370***	-1,480***	
	(75.04)	(79.42)	
South_Mal	-1,316***	-1,391***	

Table A7. (cont'd)			
	(63.76)	(69.67)	
Mundlak-Chamberlain Device variables			
kgsN_ha_mean		1.301	
		(3.079)	
N2_mean		-0.000521	
		(0.0177)	
Nsoil_a2_mean		3.592	
		(6.182)	
Nsoil_a3_mean		-5.740	
		(7.115)	
Nsoil_r2_mean		1.523	
		(6.225)	
Nsoil_r3_mean		6.395	
		(12.57)	
N2soil_a2_mean		-0.00987	
		(0.0388)	
N2soil_a3_mean		0.0739	
		(0.0468)	
N2soil_r2_mean		-0.0445	
		(0.0384)	
N2soil_r3_mean		-0.0992	
		(0.0853)	
rain_mean		0.352***	
		(0.0998)	
Nrain_mean		0.000842	
		(0.00179)	
hybuse_mean		87.95	
		(56.29)	
Nhybuse_mean		0.592	
		(1.219)	
Field ha_mean		489.9***	
		(92.46)	
Field ha^2_mean		-62.57**	
		(27.70)	
asset_mean		26.78	
		(19.29)	
asset2_mean		-1.448***	
		(0.558)	
mono_mean		237.8***	
		(66.72)	
Constant	1,822***	1,506***	1,594***
	(77.40)	(96.24)	(80.78)
Observations	8,674	8,674	8,674
R-squared	0.305	0.318	0.118

Table A7. (cont'd)			
Number of hhid			3,960

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A 8. CRE Regression Results by PN ratio group

	CRE		
	(1)	(2)	(3)
VARIABLES	**PN_0-.24**	**PN_.25-.99**	**PN_over1**
kgs Nitrogen used per ha	9.706***	27.36***	58.46*
	(3.266)	(10.33)	(29.95)
kgsN^2	-0.0159	0.0126	0.421
	(0.0170)	(0.0707)	(0.811)
rainfall (mm)	-0.235**	-0.581**	0.617
	(0.115)	(0.277)	(0.504)
kgN*total rainfall	-0.000478	-0.00407	-0.0373
	(0.00193)	(0.00512)	(0.0251)
used hybrid seeds on field y/n	68.29	519.9***	311.1
	(77.37)	(191.9)	(271.2)
kgN*hybrid use	1.319	-13.37**	-9.159
	(1.325)	(5.568)	(16.33)
field ha	-282.5**	-191.6	-572.6
	(112.5)	(259.5)	(358.5)
field ha^2	45.62	39.75	173.5
	(29.37)	(77.41)	(126.4)
hh assets	46.19	-10.78	46.29
	(40.33)	(34.10)	(34.49)
hh assets^2	0.553	0.724	-0.556
	(1.782)	(0.879)	(0.870)
Monocropped	-128.6**	23.65	656.7
	(64.61)	(168.8)	(441.1)
Good soil nutrient level	omitted	omitted	omitted
Mod soil nutrient level	8.869	-509.1	82.22
	(220.5)	(523.8)	(625.1)
Poor soil nutrient level	2.094	-221.5	200.5
	(268.9)	(524.5)	(801.6)
Good soil nutrient hold cap	omitted	omitted	omitted
Mod soil nutrient hold cap	-74.54	38.90	-498.4
	(234.7)	(512.9)	(626.5)
Poor soil nutrient hold cap	782.6	-202.4	-850.0
	(485.4)	(743.3)	(1,009)
kgN*mod soil nutrient lvl	4.888	22.45	-63.70
	(7.005)	(23.01)	(67.45)
kgN*poor soil nutrient lvl	6.559	10.60	-77.30
	(8.421)	(24.47)	(97.66)
kgN*mod soil nutr hold cap	-0.498	-12.14	112.9*
	(7.309)	(23.57)	(68.11)
kgN*poor soil nutr hold cap	-30.30*	48.86	263.3**
	(15.50)	(50.06)	(110.3)
kgN^2*mod soil nutrient	-0.0298	-0.173	0.458

Table A8. (cont'd)			
	(0.0372)	(0.206)	(1.481)
kgN^2*poor soil nutrient	-0.0534	-0.150	-0.633
	(0.0460)	(0.225)	(2.366)
kgN^2*mod soil nutr hold cap	0.0364	0.0993	-1.539
	(0.0378)	(0.212)	(1.528)
kgN^2*poor soil nutr hold cap	0.172**	-0.250	-5.165*
	(0.0683)	(0.612)	(2.798)
RiftValy_Ken	Omitted	Omitted	Omitted
Eastern_Ken	-743.6**	357.2	1.818
	(316.2)	(235.6)	(325.9)
Nyanza_Ken	-1,068***	-350.8*	-731.0***
	(336.5)	(197.4)	(164.1)
Western_Ken	89.55	-287.9**	-212.0
	(329.8)	(130.3)	(150.3)
Central_Ken	5.464	-229.5	-1,357***
	(441.9)	(219.7)	(282.4)
Central_Zam	-621.0**	-1,138***	
	(295.1)	(310.4)	
Cpperbelt_Zam	-561.3*	-1,199***	
	(304.5)	(321.2)	
Eastern_Zam	-437.9	-999.1***	
	(299.4)	(300.6)	
Luapula_Zam	-245.2	-1,410***	
	(334.4)	(296.0)	
Lusaka_Zam	-769.0**	-1,110***	
	(310.1)	(375.4)	
Northern_Zam	-494.4	-1,457***	
	(303.5)	(310.1)	
NWestern_Zam	-765.7**	-685.6*	
	(312.4)	(353.6)	
Southern_Zam	-557.7*	-516.7	
	(298.4)	(373.7)	
Western_Zam	-866.3**	-775.7***	
	(390.0)	(259.1)	
North_Mal	-1,195***	-1,447***	
	(286.1)	(203.0)	
Central_Mal	-1,174***	-1,596***	
	(286.6)	(227.5)	
South_Mal	-961.3***	-1,521***	-1,117**
	(282.3)	(178.4)	(465.0)
kgsN_ha_mean	0.926	11.12	-17.50
	(4.534)	(11.88)	(18.93)
N2_mean	-0.0256	-0.0382	0.368**
	(0.0219)	(0.0551)	(0.160)
Nsoil_a2_mean	-5.190	-4.893	14.93
	(8.979)	(23.62)	(41.25)

Table A8. (cont'd)			
Nsoil_a3_mean	-12.97	-17.91	19.53
	(10.63)	(27.29)	(60.43)
Nsoil_r2_mean	4.257	23.33	-9.094
	(9.395)	(24.34)	(40.12)
Nsoil_r3_mean	31.77*	11.17	-100.9
	(18.05)	(61.00)	(90.34)
N2soil_a2_mean	0.0271	0.0435	0.257
	(0.0496)	(0.190)	(0.474)
N2soil_a3_mean	0.0946	0.262	0.268
	(0.0616)	(0.241)	(0.736)
N2soil_r2_mean	-0.0440	-0.228	-0.221
	(0.0511)	(0.207)	(0.459)
N2soil_r3_mean	-0.230***	-1.017	1.455
	(0.0851)	(0.924)	(1.278)
rain_mean	0.164	1.686***	-0.113
	(0.155)	(0.446)	(0.744)
Nrain_mean	0.00374	-0.00674	-0.0164
	(0.00263)	(0.00728)	(0.0191)
hybuse_mean	-9.801	-69.18	420.3
	(101.9)	(294.2)	(314.4)
Nhybuse_mean	2.770	1.573	-8.775
	(1.724)	(7.097)	(12.67)
hect_mean	294.0*	327.8	407.9
	(157.0)	(305.3)	(450.5)
hect2_mean	-36.46	19.14	-167.2
	(43.11)	(88.81)	(163.4)
asset_mean	61.16	37.32	-39.08
	(50.96)	(42.90)	(42.36)
asset2_mean	-4.765	-1.840	0.389
	(3.074)	(1.124)	(1.199)
mono_mean	338.1***	-26.66	-60.82
	(96.36)	(278.6)	(491.6)
Constant	1,319***	347.5	1,164**
	(322.7)	(336.7)	(563.5)
Observations	3,052	1,035	677
R-squared	0.366	0.407	0.224

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A 9. MPP of nitrogen by phosphorus: nitrogen ratio by region within countries for successful case			
	Phosphorus:Nitrogen Ratio		
VARIABLES	0-0.24	0.25-1.0	> =1.0
Eastern Kenya	11.85	33.24	46.32
	(2.30)	(4.658)	(9.156)
Nyanza Kenya	10.48	18.22	40.46
	(2.38)	(2.890)	(6.991)
Western Kenya	12.89	16.97	32.23
	(1.22)	(1.734)	(7.571)
Central Kenya	9.990	31.05	64.74
	(2.65)	(6.209)	(15.56)
Rift valley Kenya	11.83	14.99	26.91
	(1.029)	(1.934)	(6.945)
Central Zambia	12.09	17.52	
	(0.591)	(2.560)	
Copperbelt Zambia	11.89	24.20	
	(0.896)	(5.144)	
Eastern Zambia	12.11	23.44	
	(0.930)	(3.656)	
Luapula Zambia	11.62	27.68	
	(0.737)	(4.406)	
Lusaka Zambia	11.08	13.15	
	(0.802)	(2.224)	
Northern Zambia	11.57	16.74	
	(0.721)	(2.592)	
Nwestern Zambia	11.58	31.69	
	(0.839)	(3.879)	
Southern Zambia	12.00	24.24	
	(0.872)	(3.713)	
Western Zambia	8.582	31.90	
	(1.813)	(9.583)	
North Malawi	11.46	20.54	
	(0.623)	(2.904)	
Central Malawi	12.28	16.29	
	(0.712)	(2.761)	
South Malawi	11.21	18.72	-7.970
	(0.958)	(3.457)	(22.20)
Observations	3,052	1,035	677

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