Zambia Social Science Journal

Volume 6
Number 2 *Indaba Agricultural Policy Research Institute (IAPRI) Special Issue (2015/2016)*

Article 6

2016

A Long History of Low Productivity in Zambia: Is it Time to Do Away with Blanket Recommendations?

Antony Chapoto
Indaba Agricultural Policy Research Institute

Lydia M. Chabala
University of Zambia

Olipa N. Lungu
University of Zambia

Recommended Citation

Chapoto, Antony; Chabala, Lydia M.; and Lungu, Olipa N. (2016) "A Long History of Low Productivity in Zambia: Is it Time to Do Away with Blanket Recommendations?," *Zambia Social Science Journal*: Vol. 6 : No. 2 , Article 6.
Available at: https://scholarship.law.cornell.edu/zssj/vol6/iss2/6

A Long History of Low Productivity in Zambia: Is it Time to Do Away with Blanket Recommendations?

Antony Chapoto[1], Lydia M. Chabala[2] and Olipa N. Lungu[2]

[1]*Indaba Agricultural Policy Research Institute*
[2]*Department of Soil Science, University of Zambia*

Although there have been calls to ramp up efforts to design and implement a fertiliser programme that recognises the spatial variability of soil fertility and climatic conditions in the country, Zambia like most countries in Africa, continues to rely heavily on outdated general fertiliser recommendations, which are uniform across geographic locations and crops. This could be one of the main reasons why Zambia continues to record low crop productivity despite government fertiliser subsidy programmes. Using soil analysis and household data collected in rural Zambia, this study presents a comparative analysis of location-specific fertiliser application versus blanket recommendation to demonstrate why it is important for the Zambian government to invest in area-specific fertiliser recommendations in order to raise crop productivity. As expected, the results show that soil fertility varies across the country. This was observed in all the mapped soil properties with ranges of 2.7 to 7.8 for soil pH, 0.08% to 10.1% for soil organic carbon and 1.0 ppm to 333.6ppm for soil Phosphorus. These values belong to different classes in terms of aciditys and levels of adequacy and deficiency. These results indicate that blanket fertiliser recommendations, or even liming, may not be well suited across the entire country. Instead, they support the need for Zambia to promote area-specific fertiliser recommendations. It is recommended that soil testing be promoted as part of extension messages, and that the government's Farmer Input Support Programme (FISP) should consider including soil testing as a requirement for the subsidy.

Key words:
Blanket recommendation, fertiliser, productivity, soil fertility, Zambia

Introduction

Africa continues to lag behind the rest of the world in food crop productivity. Low fertiliser use and low intensity of use are cited as two of the main factors hindering growth in agricultural productivity (FAO, 2005; Kelly et al., 2007; Guo, Koo and Wood, 2009). In response, some African countries, including Zambia, have been implementing fertiliser subsidy programmes in order to lower the cost of fertiliser and address supply issues. The main goal of such efforts has been to bolster fertiliser use and demand among many smallholder farmers who occupy a central position in agricultural production in most Sub Saharan African (SSA) countries. For example, Zambia's 2016 budget had fertiliser subsidies taking up approximately 58% of the budget for the Ministry of Agriculture (MoA) in Zambia. Despite this effort, crop productivity has risen only marginally, suggesting that there are other constraints limiting optimal fertiliser response (Chapoto and Ragasa, 2013).

Notably, there have been calls to bolster efforts to design and implement fertiliser programmes that recognise the spatial variability of soil fertility and climatic conditions in the country. Despite this observation, in the design and implementation of its fertiliser programme Zambia continues to rely heavily on the general fertiliser recommendation which is uniform across geographic locations and crops. This could be one of the main reasons why Zambia continues to record low growth in crop productivity . It stands to reason that, if farmers are applying the wrong type and amount of fertiliser on their fields, Zambia will continue to reap low yields. There have been advances in information and related technologies such as Geographical Information Systems (GIS), Global Positioning System (GPS), and data sources from remote sensing (e.g. satellite imagery and digital elevation models) but Zambia has been slow to embrace them. These advanced information and related technologies would provide almost limitless opportunities for data collection, manipulation and analysis, and would enable the country to devise policies which reflect the spatial variability of soil in an area. Embracing these approaches could be complimented by crop model simulations to determine the appropriate fertiliser rates and corresponding yield levels.

Generally, fertiliser recommendations in Zambia are based on yield response of various crop varieties in a particular location (Mwale, 1988). In this regard, seed companies base their fertiliser recommendation on the relative soil fertility status in a given locality (Zamseed, 1993) albeit in a general way with fertility status broadly classified as low, medium, or high. In many instances however, fertiliser recommendations are given as one blanket recommendation across the whole country. Fertiliser companies have also followed this general approach. For instance, Omnia Fertilizers (2013) recommended the application of the major nutrients, urea (N), P and K in the ratios 10:20:10 for maize (D compound), and in the ratios 10:12:27 for soya beans (HIPOT). The application of urea is recommended at 46%. Similarly, Zambian Fertilisers (2013) recommended the same application rates of D compound and urea in maize, and the ratios 5:20:20 for soya beans.

The foregoing examples indicate that fertiliser recommendations are mainly given as broad recommendations. With the intensification of smallholder agriculture, principally driven by government policies such as the Farmer Input Support Programme (FISP), the prescriptive fertiliser recommendations per hectare of 200kg of both D compound and urea in maize production are followed regardless of locality. While blanket recommendations may be useful, they tend to be problematic in that they do not consider factors that influence yield response of fertiliser such as climate and soil type. In a case where the soil has high levels of nutrients, blanket recommendations may lead to fertiliser wastage and economic loss to the farmer or even be an environmental hazard due to nitrate leaching (Ndlanga Mandla, 1998). On the other hand, inefficiencies in crop production resulting in low yields happen when the applied fertiliser does not meet soil nutrient status and crop requirements. The challenge therefore, is to address two key problems in the management of soil fertility, namely, soil depletion, and low yield due to inadequate levels of fertiliser use.

It is clear that several benefits accrue in agricultural production from fertiliser use. (Russell et al., 2009; Tilman et al.,(2002; Rosenstock et al.,(2013). However, many researchers have questioned the logic and sustainability of blanket fertiliser recommendations due to soil variability across the landscape (Ezui et al., 2010; Snapp et al., 2003). The many questions and misgivings regarding blanket fertiliser recommendations call for the generation of country specific empirical data on the feasibility of location specific fertiliser recommendations which consider the spatial variability of soil across the country. In addition, evidence of the economic implications of such an approach is vital in gauging the suitability of location-specific fertiliser recommendation for adoption and/or up-scaling across the country. It is against this background that this study was initiated to assess the performance and utility of location-specific fertiliser recommendations in Zambia. The general objective of the research is to pilot location-specific fertiliser recommendations in Zambia. In particular, the study had three specific objectives as follows:

i. To map the spatial variability of soil phosphorus (P), soil pH, and soil organic carbon (SOC) in Zambia.
ii. To estimate location-specific fertiliser application rates
iii. To assess maize yield response to location specific application fertiliser rates.

The remainder of the paper is organised as follows. The soil fertility status in Zambia is presented in Section 2, followed by a discussion of data and methods in Section 3. Section 4 presents the results and discussion. Finally, Section 5 discusses our conclusions and policy recommendations on moving towards location-specific fertiliser recommendations.

Soil Fertility status in Zambia

Soil fertility issues in Zambia

Declining soil fertility in SSA has continued to reduce soil productivity and poses a major challenge in addressing problems of food security (Umar et al., 2012). This has been exacerbated by prevailing extreme climate events to which Zambia is no exception. Zambia is divided into three Agro-Ecological zones (AEZs) based mainly on precipitation regimes (Figure 1).[1]

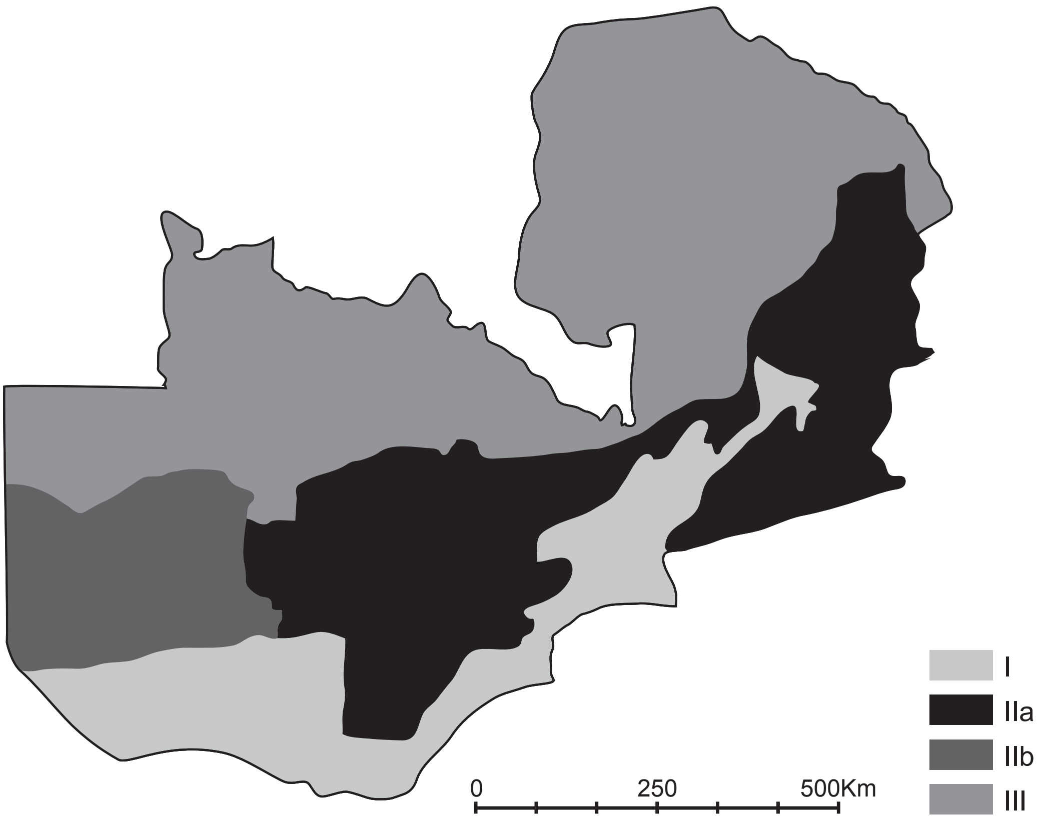


Figure 1: Zambia Agro-ecological Zone Map
Source: IAPRI, 2015

In AEZ III, for instance, there are generally highly leached and acidic soils, yet the recommendations do not take that into account (Figure 2). A study by Lungu and Dynoodt (2008) revealed that long-term annual application of urea resulted in soil acidification and decreases in exchangeable calcium (Ca) and magnesium (Mg), especially if these were already low in the soil. And yet other research has shown that crop yields on acidic and unlimed soils have declined even with the application of adequate amounts of inorganic fertilisers (Lungu and Chinene, 1993) because of its susceptibility to nutrient lock up. This was documented by Mambo and Phiri (2004), when they produced the national soil acidity map of Zambia (Figure 2).

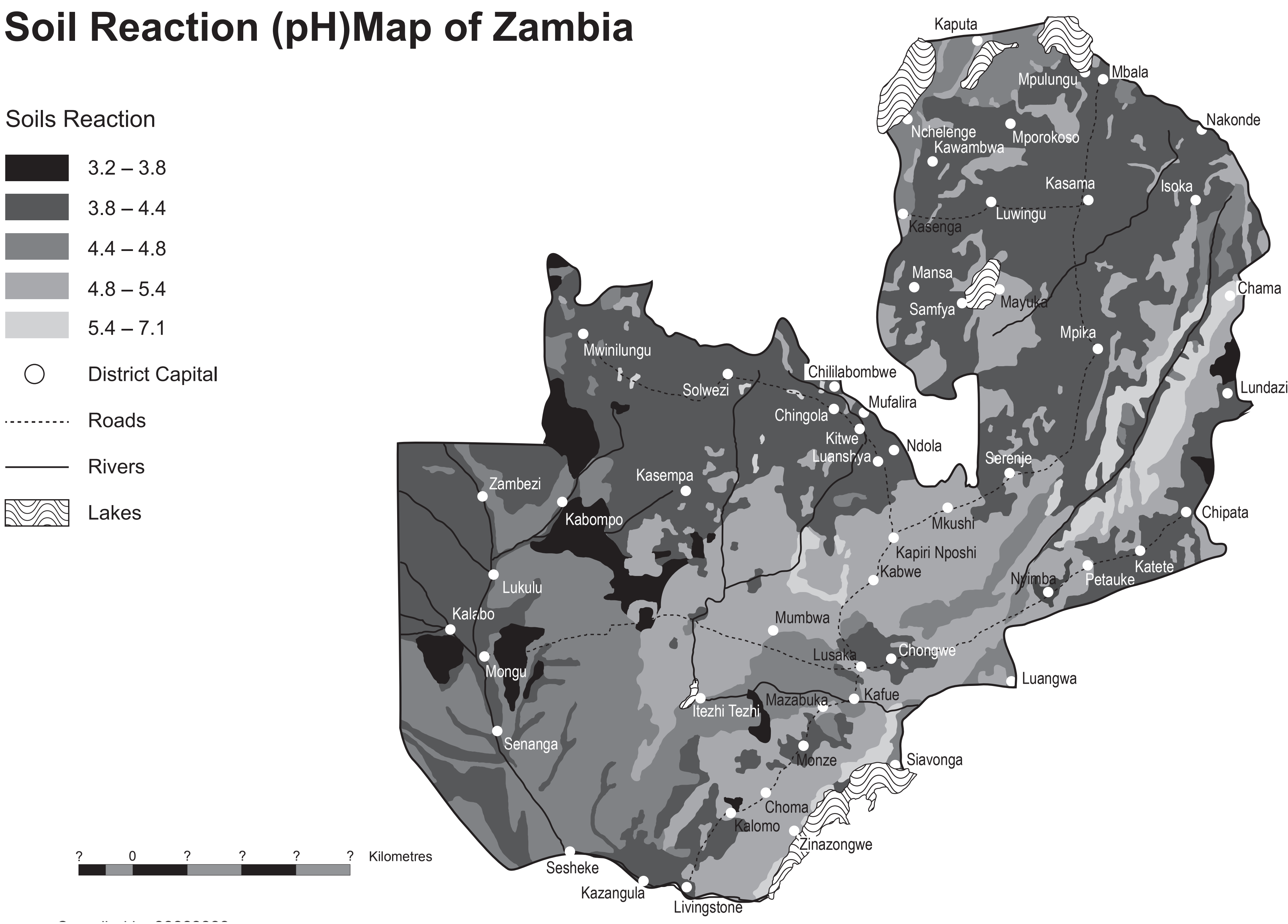


Figure 2: Soil Acidity Map of Zambia Source: Mambo and Phiri (2004)

Although, this map is more than ten years old, it illustrates that the soil in the northern region and some parts of the western region of the country were extremely acidic with pH values less than 4.5. This means that areas in this locality require lime, an approach that has been promoted by various stakeholders. However, it should be noted that other than acidity, soil type is an important aspect of optimal crop production and fertiliser utilisation.

Generally, soils in the high rainfall region III are heavily leached and acidic, while those of region II are believed to be fairly fertile and those of region I are mostly sandy and less fertile (JAICAF, 2008). Further, most of the agricultural land across the country lacks the much required organic matter, which is crucially important for the fertility of any given soil. The lack of this organic matter affects the physical, chemical, and microbial health of the soil.

History of Blanket Fertiliser Recommendation in Zambia

Commercial agricultural production in Zambia was mainly done along the line of rail in the early 1980s. Soil samples were taken from these production sites and fertiliser recommendations were made based on the preliminary results (McPhillips, 1983, Lungu, 1987). This led to increased yields in most areas. The small-scale farmers also greatly contributed to crop production and recommendations such as lime application were made to help enhance their productivity (McPhillips and Prior, 1979 in Lungu, 1987).

In order to encourage massive production in all parts of the country, generalised or blanket recommendation were employed. It was assumed that nutrient requirements of the different soil types would fall within these recommendations. To date, there has not been enough effort to revisit this and update the recommendations based on updated soil and plant requirements findings. Some fertiliser companies in the country do, however, carry out soil tests in places where they put up their demonstration sites. With the long-term use of the soils, there have been tremendous changes in their status and one of the well known changes is the inherent fertility decline. Yields have stagnated and declined in some parts of the country and when blanket recommendations are made, they do not consider the soil's nutritional status and the plant requirements as a whole. This continues to increase fertiliser use inefficiencies in terms of costs and nutrient management.

Soils of Zambia

Soil Type

According to Eswaran et al., (1997), most of the agricultural soils in Zambia are of the orders Alfisols, Ultisols and Oxisols. The national soil map of Zambia shows that Acrisols are the dominant soil grouping in AEZ III with mainly Gleysols occurring in very slight combination with Histosols in the swampy areas (Figure 3). The World Reference Base for Soil Resources (WRB) in 2006 states that Acrisols are strongly-weathered acid soils with low base saturation at some depth, and that they have higher clay content in the subsoil than in the topsoil. Adapted cropping systems with complete fertilisation and careful management are required for farming on such soils. On the other hand, Gleysols are wetland soils that, unless drained, are saturated with groundwater for long periods as is the case in the swampy areas of AEZ III. The main limitation to the use of Gleysols is the necessity to install a drainage system to lower the groundwater table. Adequately drained Gleysols can be used for arable cropping, dairy farming, and horticulture.

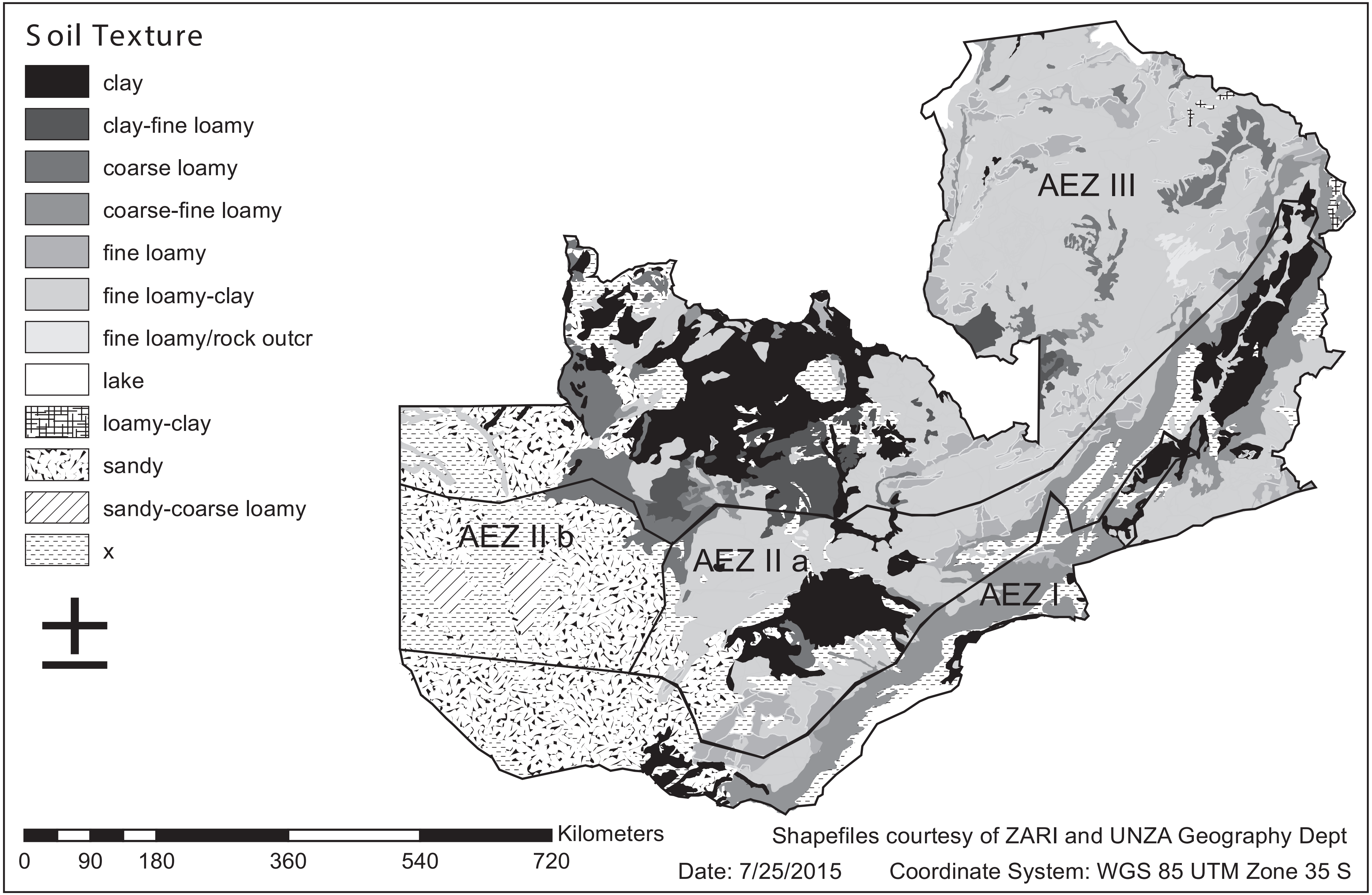
In AEZ IIa, Lixisols are dominant in the areas around Kapiri Mposhi, whilst Regosols and Leptsols are dominant around Mumbwa, and Vertisols characterise most of Southern Province (Figure 3). Generally, Lixisols have a higher clay content in the subsoil than in the topsoil although a high base saturation and low-activity clays occur at certain depths. Degraded surface soils have low aggregate stability and are prone to slaking and/or erosion when exposed to the direct impact of raindrops. The low absolute level of plant nutrients and the low cation retention by Lixisols means that recurrent use of fertilisers and/or lime is a precondition for their continuous cultivation (WRB, 2006). Vertisols on the other hand are churning, heavy clay soils with a high proportion of swelling clays. These soils form deep wide cracks from the surface downward when they dry out. The physical properties and the soil moisture regime of Vertisols represent serious management constraints. The heavy soil texture and domination of expanding clay minerals result in a narrow soil moisture range between moisture stress and water excess.

In AEZ IIb the dominant soils are the Arenosols whose main characteristic is the coarse texture, which accounts for the high permeability and low water and nutrient storage capacity. Arenosols offer ease of cultivation, rooting and harvesting of root and tuber crops. AEZ I is dominated by Arenosols on the western part while Leptosols dominate most of the land in the valley areas (Figure 3). Leptosols are very shallow coarse soils often occurring in stony areas. Leptosols on hill slopes are generally more fertile than their counterparts on more level land (WRB, 2006). One, or a few, good crops could perhaps be grown on such slopes but at the price of severe erosion.

Soil texture

In the case of soil texture, the soils in the northern section of AEZ III are dominated by fine loamy clays, whereas much of the western part is dominated by clay soils with some patches of sandy and loamy soils. Most of the soils in AEZ IIa are of sandy texture although a section of it has sandy soils (Figure 4).

Figure 3: Soils of Zambia Source: Ministry of Agriculture Soil Survey Section (1991)



Further, the AEZ I is dominated by coarse fine loamy soil textures with the areas around the lake having mainly soils of a fine loamy to loamy textures.

The variation in the soil texture and general soil grouping shows that there exists a wide variety in soil occurrence across the country. This means that specific nutrient requirements and fertiliser application are necessary for efficient crop production, rather than blanket recommendations. Among the nutrients required for plant growth, most of the major nutrients are found in scanty amounts in the soil. For instance, a study by Yerokun (2008) reported that most Zambian agricultural soils had small amounts of phosphorus (P) in them. In the same study, soils of different origins showed similar trends in their amount of available phosphorous. The low levels of phosphorus availability was attributed to the low organic matter content, nature of the soil, as well as the microclimates under which they existed.

The findings by the aforementioned study were consistent with those of Malama (2001) who found that most soils in the high rainfall regions of the country had low amounts of nutrients due to high levels of leaching. Additionally, the soils in AEZ III which receives rainfall above 1200mm per annum are usually acidic and have a high amount of exchangeable Aluminium (Al) and Hydrogen (H). Despite the existence of a number of studies showing the major soil fertility problems in the study areas, fertiliser recommendations have not been revised in accordance with the evidence provided by these studies. In optimal cases, the application rates are based on the yield targets, where one must apply more to realise high yields. However, Xu et al. (2009a; 2009b) reported that the maize yields were not economically reliable under the small-scale farmers who received the subsidised inputs, suggesting that something was wrong with blanket recommendations. Generally, the blanket recommendation of urea and D compound - which maize growers generally use - has not resulted in an increased production rate. This in turn means that the country is not getting an optimal return from its fertiliser subsidy investments.

Some technologies addressing challenges in soil fertility

A number of technologies and innovations have been suggested to address the issue of nutrient imbalance and general soil fertility in soils. Erestein (2003) proposed that crop cover mulching would ameliorate the soil fertility status of soils. The mulch if incorporated well in soils, can contribute to the soil organic carbon content. This would in turn improve the fertility of the soil. In a similar study on Zambian acidic soils, Malama, (2001) found that most soils in the high rainfall area had high exchangeable acidity, aluminium, and low phosphorous. Other efforts include conservation agriculture (CA), which still has a low adoption levels among the smallholder famers in Zambia. Under CA, a number of practices have been suggested such as the use of cover crop mulches and

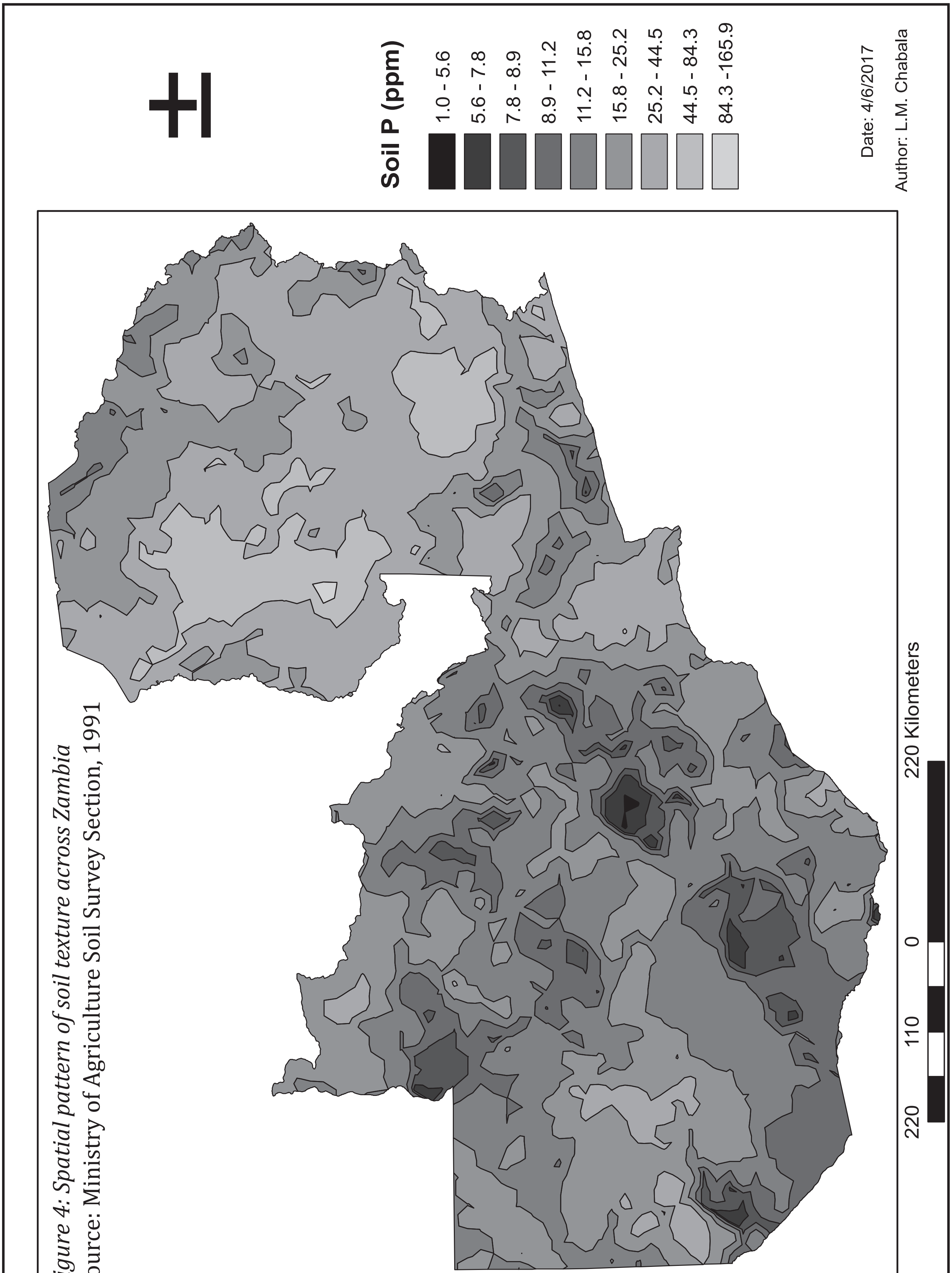


Figure 4: Spatial pattern of soil texture across Zambia
Source: Ministry of Agriculture Soil Survey Section, 1991

incorporation of Faderbia albida trees into the farming systems. According to Umar et al., (2013), and Shitumbanuma, (2012), the incorporation of Faderbia albida trees in the CA systems had a positive effect on the nutrient levels of the soils and subsequently on crop yield. Similarly, a study by Siame et al., (1998), on the highly acidic Oxisols of northern Zambia showed that the incremental addition of nitrogen through intercropping maize with beans increased the maize yield.

Despite these innovations showing positive productivity results, they have not been used on a sustainable basis by smallholder farmers in the country. This may largely be due to resource constraints inhibiting smallholder farmers from investing in simple technologies that can help improve fertiliser response rates. The government's subsidy programme has helped improve this situation but with limited success, as the packages given to farmers disregard spatial soil variations in the country. Inorganic fertilisers which are in the form of urea and D compound are mostly used across the country, and are applied at a general rate of 200kilograms (kg)/ha in maize production. This application rate is recommended regardless of the soil types and needs.

Data and Methods

Data

This study uses data from a random sample of households interviewed during the Rural Agricultural Livelihoods Survey (RALS), implemented in May/June 2012 by the Indaba Agricultural Policy Research Institute (IAPRI) in collaboration with Central Statistical Office (CSO), and MoA.

The sampling frame for the RALS 2012 survey was based on the 2010 Census of Housing and Population. A stratified two-stage sample design was used for the RALS 2012 sampling. The first stage involved identifying the Primary Sampling Unit (PSU), Standard Enumeration Areas (SEAs) with a minimum of 30 agricultural households. At the second stage, all households in selected SEAs were listed and agricultural households identified. Listed agricultural households were then stratified into three categories; A, B, and C, on the basis of total area under crops; presence of some specified special crops; numbers of cattle, goats and chickens raised; and sources of income. Systematic sampling was then used to select 20 households distributed across the three strata in each SEA. Within the selected 20 households, four households were randomly selected for soil sample collection from the largest maize field. For the sub-sample, an additional module was added to obtain information about the particular plot and other household economic data for the 2011/12 agricultural season. In particular, the module collected additional specific information about production and farm management practices, including fertiliser use for that particular plot. In addition, the plot size was physically measured with the aid of a GPS device.

Sample size

A total of 1,714 soil samples and plot surveys were completed from 1680 households. The intention was to collect one sample per household, but more than one sample was collected from some fields that had noticeable differences in terms of slope or soil colour, and texture. Twenty-six households provided two samples each and four households provided three samples, making the total of soil samples collected greater than the number of households. However, we were unable to determine the proportion the plots covered by these multiple sample households. Hence, they calculated a simple average across samples instead of a weighted average.

Soil collection and analysis

Soil samples were collected by enumerators and their supervisor, all of whom were trained by the Zambia Agricultural Research Institute (ZARI) (CSO/MAL/IAPRI, 2012 for details). Essentially, each sample was made out of a composite mixture of 10-20 sub-samples collected within the boundaries of the plot, following the prescribed collection depth, pattern, and size of the plot. Each sub-sample was in itself a composite of equal parts soil in the 0-10 cm and 10-20 cm depth (i.e., the depth of maize roots), and for fields planted using ridge tillage, samples were taken directly from the ridges (Burke et al., 2015). The location of soil sampling points across the country is shown in Figure 5.

The soil samples were analysed at ZARI for texture, soil organic carbon, phosphorus, pH and other soil attributes using standard laboratory procedures. Soil pH was determined using a standard pH meter in CaCl2 according to the method described by McNeal (1982). Soil organic carbon (SOC) was determined by the Walkley and Black procedure, and reported as soil organic matter (SOM) by multiplying the SOC by a constant conversion rate of 1.714. The available phosphorus was determined by the Bray and Kurtz 1 method (Bray and Kurtz, 1945). Cation exchange capacity (CEC) was analysed using the ammonium acetate method at pH 7.0, and measurement of the sorbed ammonium (NH) by titration following the exchange of sorbed NH with excess sodium chloride (NaCl). To evaluate the precision of the soil analysis results, 2% of the observations were randomly selected for a second round of testing and comparison to initial measurements. Burke et al., (2015), presents the detailed results of the comparison of the second round testing and the first testing. They concluded that the test results had acceptable levels of precision but could not attest to the accuracy of the laboratory's results because resources did not allow for blind testing of a random sample by another

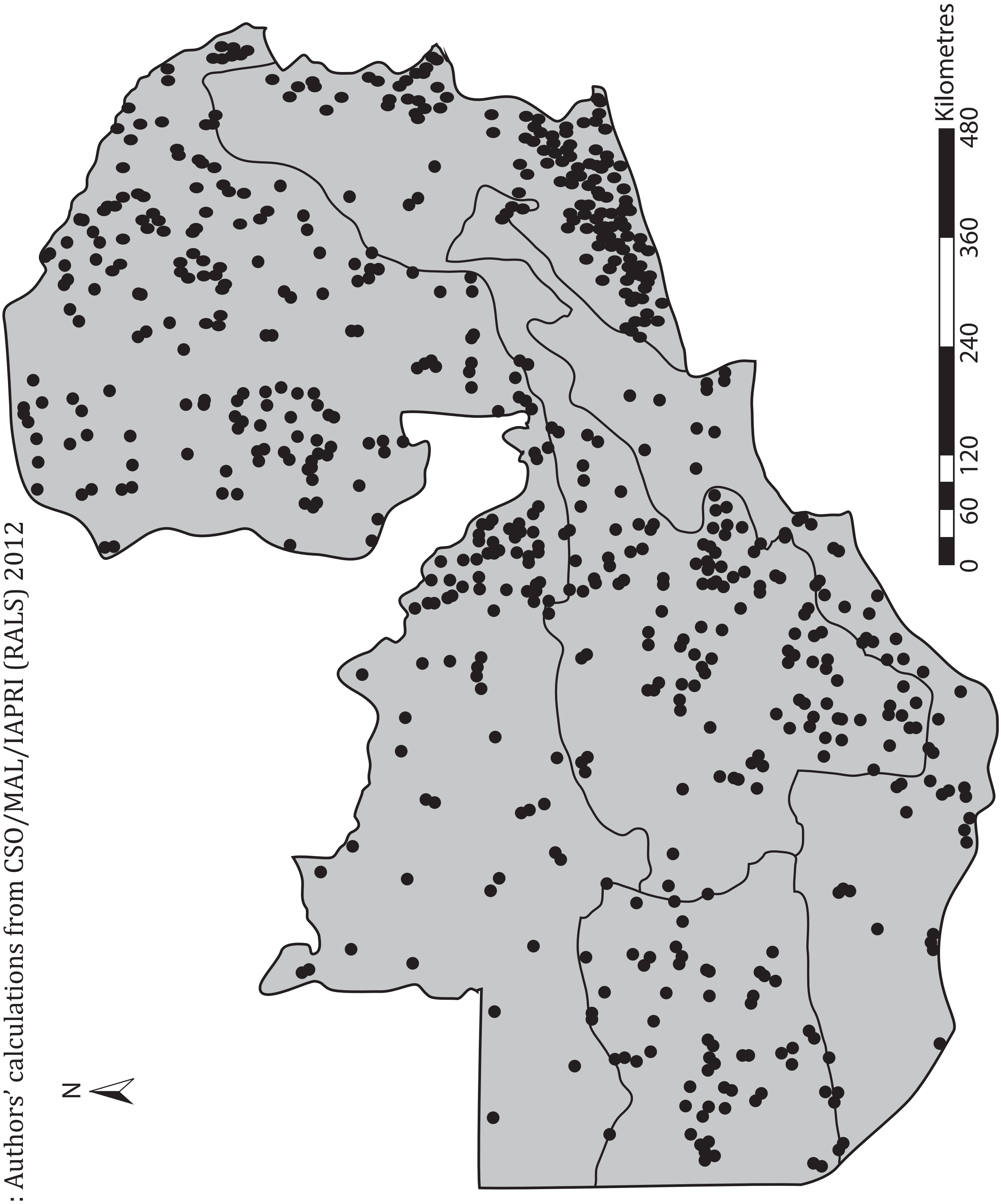


Figure 5: Location of soil sampling points
Source: Authors' calculations from CSO/MAL/IAPRI (RALS) 2012

independent laboratory. This study uses the results with this small caveat in mind, and recommends that future studies strive to verify the accuracy of the laboratory test in addition to the second round of testing.

Mapping spatial variability of soil phosphorus, pH and soil organic carbon

An initial 1,715 geo-coded soil samples were examined for use in this analysis. As a first step to mapping spatial variability of phosphorous, pH, and SOC, preliminary data cleaning was done. During the screening, all the data points that were falling outside Zambia were removed - this was attributed to errors in entering GPS coordinates during data entry. Further screening was done by drawing box plots of data. Outliers were identified visually as individually plotted rather than part of the whiskers in the box plots. Where such outliers were found, all suspect values were removed. Thus, after screening, a total of 1,593 data points were used to map the spatial variability of soil acidity (pH) and phosphorus, and 1,588 for SOC. With the screening completed, summary statistics were then generated to provide a basic understanding of the characteristics of soil phosphorus, SOC, and pH across the country.

Further data exploration was done using the histograms to analyse the distribution of the data for phosphorous, pH, and SOC. This exploration was relevant so as to select an appropriate modelling approach in the mapping of the soil properties. Where the data was not normally distributed, it was log transformed as was the case for soil phosphorous. This transformation of data to normal distribution was required because the method used in this study as discussed below relies on the assumption of stationarity which requires in part that all data values come from distributions that have the same variability (ESRI, 2013). In the final model output, the predicted soil properties were transformed back to the original scale in the interpolated surface.

The map of soil phosphorous and soil acidity was generated using Ordinary Kriging (OK). OK is one of the geostatistical models that use a set of statistical tools to predict the value of a given soil property at a location that was not sampled (Johnston et al., 2001). OK is said to be an exact interpolator in the sense that interpolated values, or their local average, coincide with values at the sampled locations (Burrough and McDonnell, 2004). The predicted property (x0), at an unsampled location s0 using observations Z(xi), i = 1,..., n was given by equation 1:

$$\hat{Z}x_0 = \Sigma_{i=1}^{n} \lambda i . Zx_i \qquad (1)$$

Where λ_i is the kriging weight.

The map of SOC was generated using inverse distance weighting (IDW). The IDW was selected as the appropriate method for generating a map of SOC because the data did not fulfill all the basic assumptions of kriging. The assumption in IDW is that the value of a soil property in this case SOC, at the location that was not sampled is a distance - weighted average of data points occurring within a neighbourhood (Bolstad, 2009). Therefore, points that are further away from the location being estimated are given less weight compared to those points that are nearer. The values at unsampled locations are estimated by equation 2 below:

$$Zj= \frac{\sum_i \frac{Z_i}{\mathrm{d^n}_{ij}}}{\sum_i \frac{1}{\mathrm{d^n}_{ij}}} \qquad (2)$$

Where Z_j is the estimated value for the unknown point at location j, d_{ij} is the distance from a known point i and n is a user defined exponent. The number of points used in the interpolation were 10 as the minimum with a maximum of 15 points. It should be noted that the farther away the point (larger d_{ij}), the smaller the weight ($1/d_{ij}$), thus the less the influence that point had on the estimated value at the unknown point.

Assessment of model performance used in map production

The assessment of the Kriging models for soil pH and phosphorous is based on the Leave Out One Cross Validation (LOCV). The indices used in the LOCV were the average standard error (ASE), the root mean square error (RMSE), and the RMSE standardised. The goal is that an acceptable model for mapping should have the average standard error close to the RMSE, and the RMSE standardised should be close to one (1) if the model is correctly assessing the variability in the predictions. The statistical significance of IDW used to map SOC was evaluated based on the mean error and the RMSE. The goal in IDW is to have a mean prediction error close to zero (0) which would indicate that the predictions were not biased. The detailed geostatistical modelling procedures applied to map the spatial variability of soil phosphorous, pH, SOC, OK and inverse distance weighting will be addressed in a separate paper.

Generation of location specific fertiliser recommendation

Once the soil maps were produced, location-specific fertiliser recommendations were done. This was achieved by considering the soil phosphorus values in the soil map. Potassium was kept constant because it was assumed that it is not limiting in most Zambian soils. Further, since no soil test data was available for nitrogen, this nutrient was varied on 50% incremental basis from the actual household fertiliser application rate. Thus, with information on soil phosphorous and the varied rates of N, location-specific fertiliser recommendations were generated based on the nutrient levels of each of the soil units represented in the map.

Results and Discussion

Spatial variability of soil phosphorus

Table 1 presents the summary statistics for soil phosphorous, pH, and SOC, whilst Table 2 shows the prediction errors associated with the models used to generate the soil maps. The results in Table 1, column A show that the mean soil phosphorus was 23.73 ppm while the standard deviation was 29.15 ppm indicating a high variation around the mean. The minimum soil phosphorous value was 1.06 ppm while the maximum value was 333.63 ppm. The soil phosphorous levels were skewed to the left as indicated by the coefficient of skewness of 4.50 and coefficient of kurtosis of 34.3.

The spatial variation of soil phosphorous is shown in Figure 4. The map shows big spatial variation of soil phosphorus across the country. Soils in the Northern and Eastern parts of the country have P values concentrated around the range of 15.8 – 84.3 ppm. The levels of phosphorous were lower in Central Province and surrounding districts particularly in Mumbwa, Kabwe, Kasempa, and Itezhi-tezhi districts, where values ranged from 1.1 to 7.8 ppm. It was further observed that intermediate values of soil phosphorous predominate in most of Southern Province particularly in Mazabuka, Choma, and Kalomo where soil phosphorous ranged from 11.2 to 25.2 ppm. However, it should be noted that the prediction errors were very large. For instance, the RMSE standardized was 0.7 indicating that the Kriging model was underestimating the variability of phosphorous at locations that were not sampled (Table 2). Despite this shortcoming, the results show that there is high variability in soil phosphorus in the country, highlighting that blanket fertiliser recommendations are too generalised to lead to improved crop productivity.

It should be noted that soil P is one of least available plant nutrients in Zambian soils. This is particularly so in soils of AEZ III where pH values of less than 5.5 are common. Under such conditions, P availability is limited by aluminium and iron fixation usually associated with soil parent material. The generated soil P map (Figure 6) however shows that P levels were higher in the northern part of Zambia which is generally associated with high acidity levels as demonstrated in the soil pH map (Figure 7) produced in this study.

This is a rather conflicting result considering that soils in northern Zambia are considered limited in terms of available P. This is noteworthy as P ions can increase to considerable concentrations in highly fertilized soils (Hinsinger, 2001). Further, it has been shown that while both parent material and land use are responsible for soil P content, only the effect of parent material permeates the entire soil profile while land use only affects the surface horizon (Dufey et al., 2010). The effect of land use also may have contributed to the observed P levels in northern Zambia since most of the soil samples were collected from the 0 – 20cm soil layer which is most influenced by land use.

	Phosphorus (ppm)	**Soil pH**	**SOC (%)**
	(A)	**(B)**	**(C)**
Mean	23.73	5.4	1.09
Minimum	1.06	2.7	0.08
Maximum	333.63	7.8	10.1
Median	15.0	5.4	1.04
Standard deviation	29.15	0.68	0.46
1st Quartile	8	5	0.81
3rd Quartile	28.06	5.8	1.33
Skewness	4.52	0.31	5.19
Kurtosis	34.37	3.72	95.7

Table 1: Summary statistics for soil Phosphorous, pH, and SOC
Source: Authors' computation

	Phosphorus (ppm)	**Soil pH**	**SOC (%)**
Mean	0.0011	2.639	-0.0035
Mean standardised	0.002	0.038	-
RMSE	0.5644	27.54	0.43
Average standard error	0.566	44.99	-
RMSE standardised	0.994	0.7	-
Method	Kriging	Kriging	Inverse Distance Weighting

Table 2: Prediction errors for the mapped soil properties
Source: Authors' computation

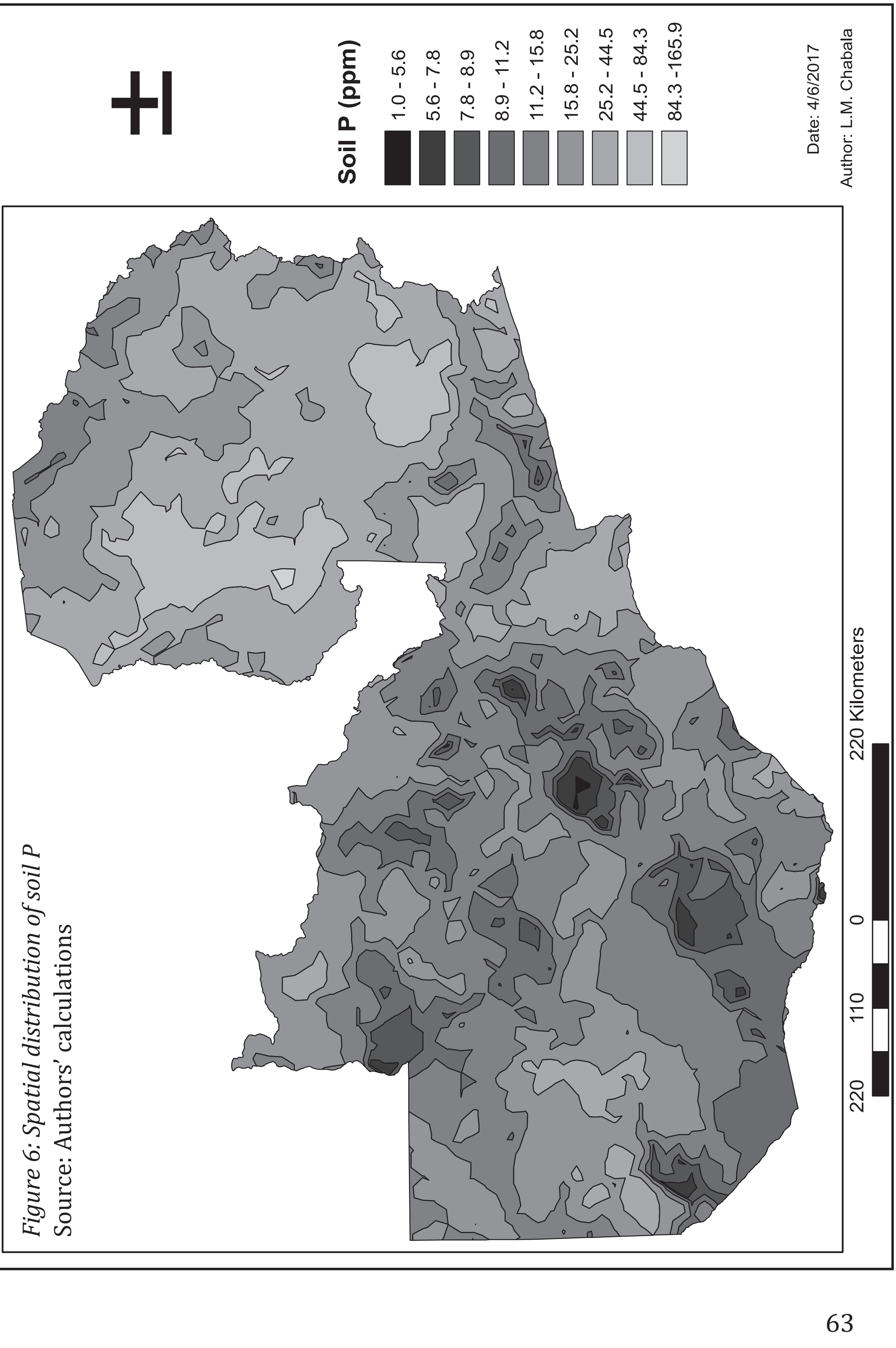


Figure 6: Spatial distribution of soil P
Source: Authors' calculations

Soil pH

The spatial variability of soil pH across the country is shown in Figure 7. The results show that ASE was 0.5660, which was approximately equal to the RMSE of 0.5644 (Table 3). Further the RMSE standardised was close to one (1). This means that the predicted soil acidity map was correctly assessing the variability of soil pH. The soil pH in most parts of Luapula and Northern provinces was generally in the range of 4.7 – 5, while a small part of the northern region, and the westernmost parts of the country recorded the lowest pH between 2.7 – 5.2. In contrast, most of the Eastern Province and parts of southern Zambia had pH values in the range of 5.5 – 5.8. These ranges represent the optimal levels for crop production, and suggest that in these areas liming cannot be generalised, but should be site-specific. Intermediate values were observed in the rest of the country which points to the need to avoid generalisation in terms of lime application. Additionally, the generated soil pH map reflects the acidic nature of the soils in AEZ III. This means that lime application is imperative in this region to ensure that crop yields do not decline due to nutrient lockup in un-limed soils

Soil organic content

In the case of SOC, it was observed that most of the western parts of the country were deficient in SOC. The values mainly ranged from 0.08% to 0.9% (Figure 8) which levels reflect the sandy nature of soils in this region. The rest of the country generally had marginal values of SOC, with values ranging from 1.03% to 1.85%. Only a small section of the country had adequate values of SOC with values above 2.7%. Normally the threshold for SOC in agricultural production is 2.5%, hence most of the soils in Zambia, like most tropical soils had very little SOC.

These results suggest that conservation measures that require preservation of organic materials (e.g. crop residues) should be promoted as a means of maintaining the carbon pool in the soil. The implication of these results is that certain practices that lead to depletion of SOC (such as burning), should be discouraged.

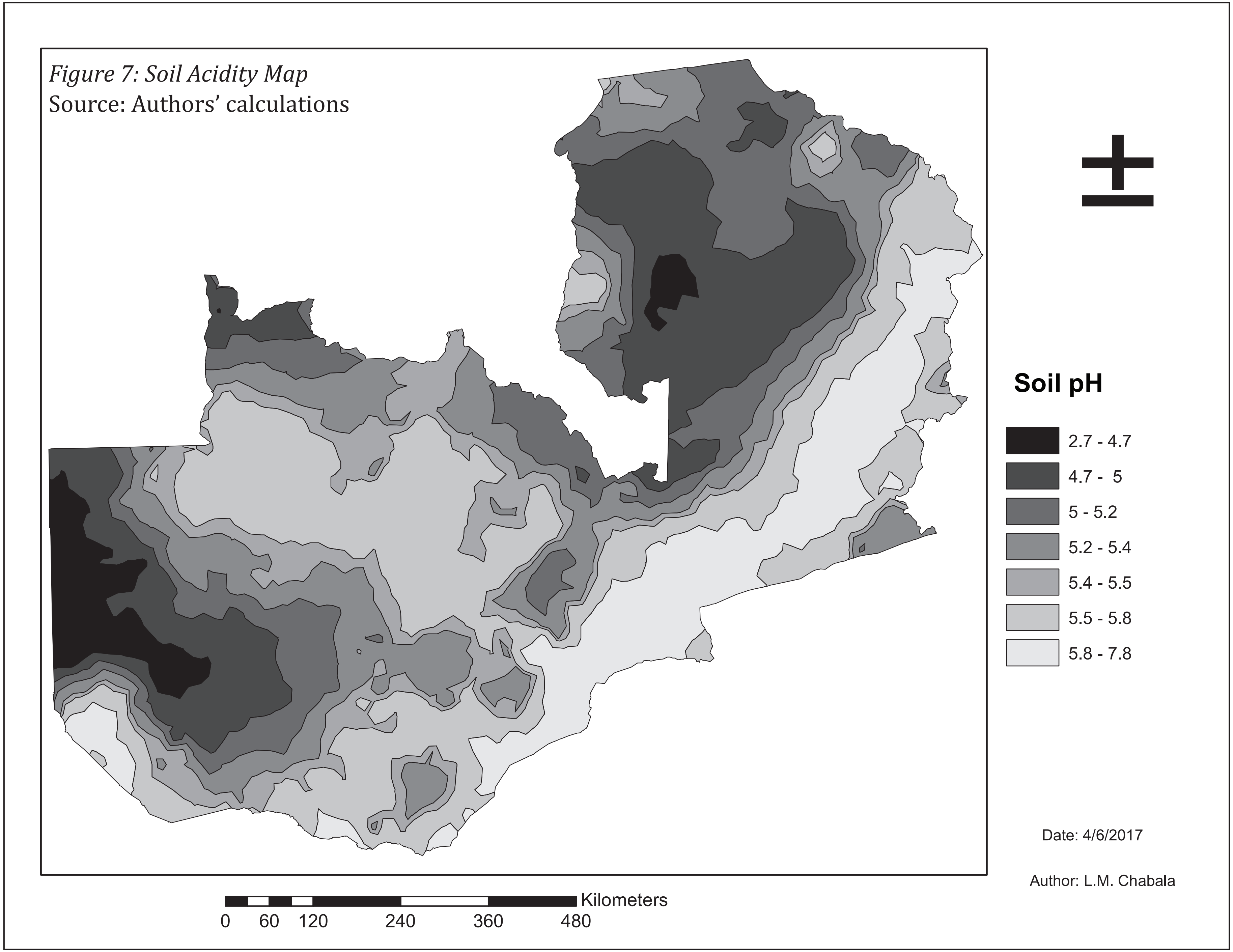
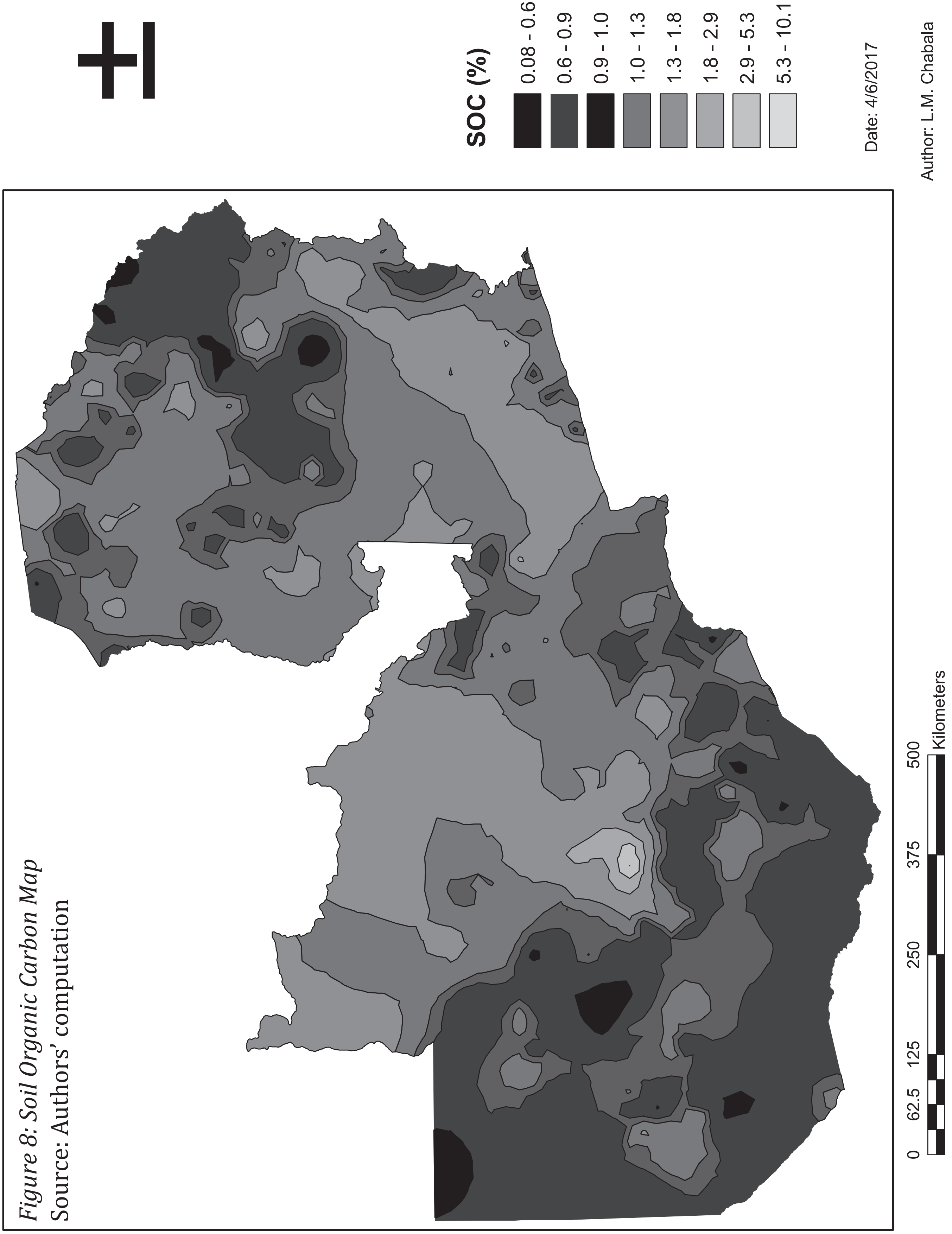


Figure 7: Soil Acidity Map
Source: Authors' calculations



Date: 4/6/2017

Author: L.M. Chabala

Figure 8: Soil Organic Carbon Map

Source: Authors' computation

Location specific fertiliser recommendation

Table 3 shows the categorisation of soil phosphorous at national level. Generally, Central, Western and Southern provinces were severely deficient to moderately deficient in soil phosphorous. The rest of the country particularly the northern section had adequate levels of phosphorous, meaning fertiliser application rates need to be varied across the country to suit the phosphorous levels.

Using the soil phosphorous classes generated from the soil analysis results, it was recommended to apply 300kg/ha of D compound fertiliser in the severely deficient soils and 200kg/ha in soils that have moderate and adequate phosphorous, whilst the current recommendation countrywide is 200kg for D compound. From this simple aggregated analysis, the results suggest that in severely deficient soils, farmers should have applied more fertiliser, whilst the blanket rate was adequate in the moderate and adequate soil phosphorous soils. The available soil analysis results showed that plant available phosphorous was low, and therefore classified according to the classes given in Table 3.

P (mg/kg)	Average P (mg/kg)	kg P/ha	Category	Field Interpretation
1-5.6	3.3	8.58	Low	Severe Deficiency
5.6-7.8	6.7	17.42	Low	Severe Deficiency
7.8-8.9	8.35	21.71	Low	Severe Deficiency
8.9-11.2	10.05	26.13	Low	Severe Deficiency
11.2-15.8	13.5	35.1	Medium	Moderate Deficiency
15.8-25.2	20.5	53.3	Medium	Moderate Deficiency
25.2-44.5	34.85	90.61	High	Adequate
44.5-84.3	64.4	167.44	High	Adequate
84.3-165.9	125.1	325.26	High	Adequate

Table 3: Analysed Soil Phosphorous and Interpretation of Results
Source: Authors' calculations

Fertilisation with phosphorous would be required at a level to restore the soil fertility to adequate status, and also to meet the crop requirement for target yields on lands represented by soils in the moderate soils category. Generally, 60 kg/ha Phosphorous pentoxide (P2O5) would be required to correct the deficiency on severe deficiency soils for maize production (Havlin et al., 2004). In order to maximise the yield potentials for maize, this can be achieved by applying D compound fertiliser at the rate of 300 kg/ha to avoid nutrient mining. In soils with adequate P, fertilisation should be maintained to achieve target yields, and avoid a decline in soil fertility (Wasonga et al., 2008). Both fertilisers should be banded or applied to the planting furrow or basin. In addition, about 100 kg/ha N as ammonium nitrate applied as top dressing should be adequate. General fertiliser recommendations such as 200 kg/ha of mixed fertiliser such as D compound followed by 200 kg/ha of urea or ammonium nitrate should suffice for maize on these soils to achieve yields above 4 tons/ha. However, this recommendation would be best based on the actual nitrogen requirements of the soil. Furthermore, land husbandry practices that increase soil organic matter content such as retention of crop residues on land, manuring and crop rotation, especially with legumes, and use of lime to raise the soil pH, should be encouraged in acidic soils to allow crops to thrive better in these soils.

Table 4 shows the distribution of farmers based on D compound fertiliser application rates by soil phosphorous status, compared to the area-specific fertiliser recommendation by soil phosphorous status. In general, the results show that more than 40.8% of the households did not use any fertiliser, whilst more than 90% in severe deficiency phosphorous soils used less than the recommended amount. Furthermore, about 25% of households in areas with moderate to adequate phosphorous used more than the 200kg/ha of D compound fertiliser.

Soil P Status	**Number**	**Did not use fertiliser**	**Percentile of Compound D fertiliser per Hectare (kg/ha)**				
			Mean	**25th**	**50th**	**75th**	**90th**
Severe	631	40.8%	141.00	80.00	123.46	200.00	246.91
Moderate	494	30.2%	162.71	100.00	150.00	200.00	266.67
Adequate	459	36.3%	168.56	100.00	164.61	200.00	300.00
Full sample	1584	34.5%	156.29	90.00	133.33	200.00	246.91

Table 4: Compound D Fertiliser use by Soil Phosphorous Status
Source: Authors' calculations

Figure 9 shows the average yield differences by soil P status. In general, the results show that irrespective of soil P status the average maize yields with fertiliser application are more than 1000kg/ha higher than the yields obtained with no fertiliser application. With fertiliser, soils with adequate P had slightly higher yields compared to medium and severe deficiency P soils.

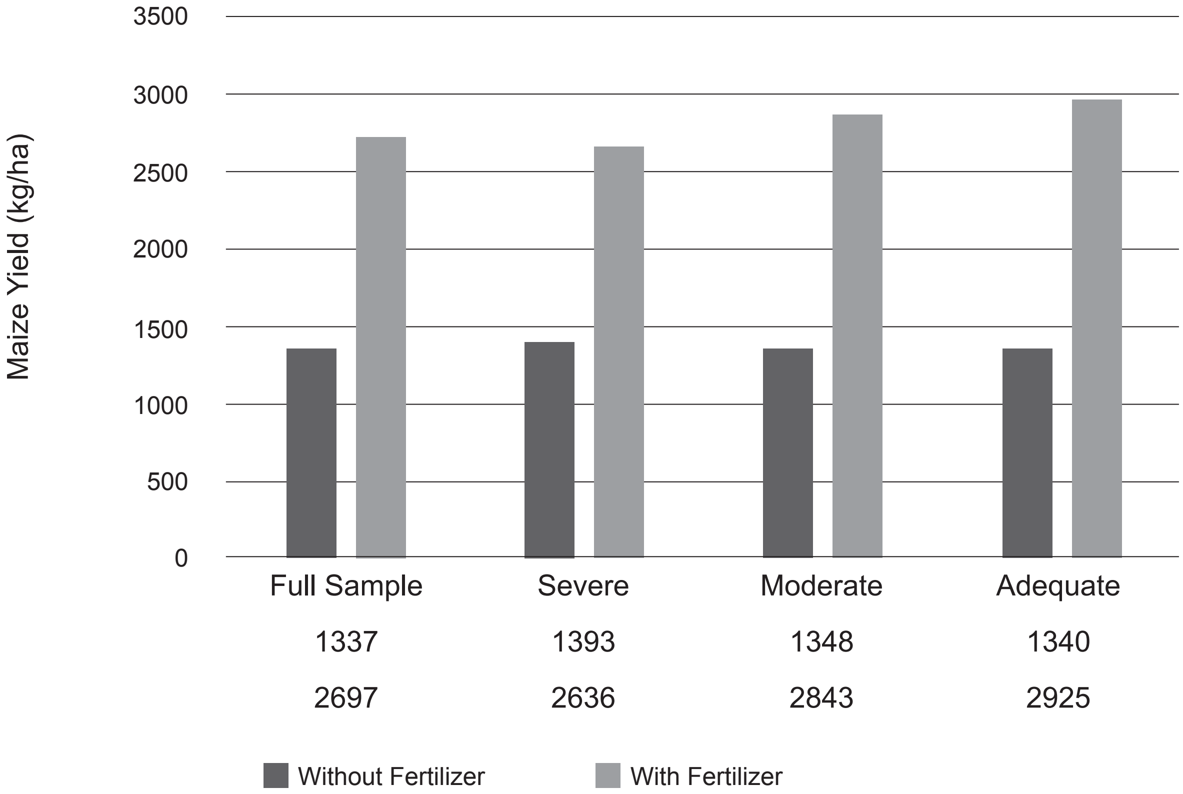


Figure 9: Maize yield with and without fertiliser
Source: Authors' computation

Economics of fertiliser use

From an agronomic perspective, one would expect to see a declining trend in maize yield with higher level of fertiliser application (diminishing returns). However, it was not possible to clearly show this trend for all the soil types as our data was not based on field fertiliser trials, but rather on self-reported yields and applications rates by the farm households. Figure 10 shows that there are diminishing returns of fertiliser use. However, apart from the severe deficiency phosphorous status fields, we were not able to see the inflexion maize yield points for medium and adequate phosphorous soils. The researchers further note that the adequate and moderate phosphorous soils have plant-available phosphorous in the soil solution, which the plants readily use during the critical growth stages.

The incremental maize yield resulting from additional application of fertiliser shown in Figure 11 is calculated by taking the maize yield for a particular fertiliser application level, and subtracting the maize yield when no fertiliser is applied, and dividing the result by the rate of fertiliser applied. For example, if the average yield in fields with no fertiliser is 1366 kg/ha, and in a field where the farmer applied 200kg/ha is 2031 kg/ha, then the kg increase in maize yield per kg of fertiliser applied is given by (2031- 1366) ÷ 200 = 4.1.

Thus, at 200kg/ha, the additional increase in maize yield for every kilogram of fertiliser is 4.1kg. If the law of diminishing returns did not apply, then the increase in yield for different rates would be the same. In this regard, Figure 12 shows diminishing returns with increased use of fertiliser for all types of soils. However, the incremental yield benefit is more limited in severe deficiency phosphorous soils compared to the medium and adequate phosphorous soils. The problem of high phosphorous fixation is generally experienced in acidic soils with sesquioxides and rarely in calcareous. (Sanchez, 1980).

Generally, if a phosphorous-deficient soil can be managed by 20-50kg/ha, then it is not problematic, more than 300kg/ha, however, poses an economic threat. Phosphorous deficiencies affect plant growth and can be very detrimental to the plants in that sometimes they may not recover (Grant et al., 2001). This leads to reduced yields as the phosphorous is present in inaccessible forms in the soil due to formation of insoluble compounds with aluminium (Cakmak, 2002). This may explain why the yield response in severe deficiency phosphorous soils was lower than in moderate and adequate soils as shown in Figure 11.

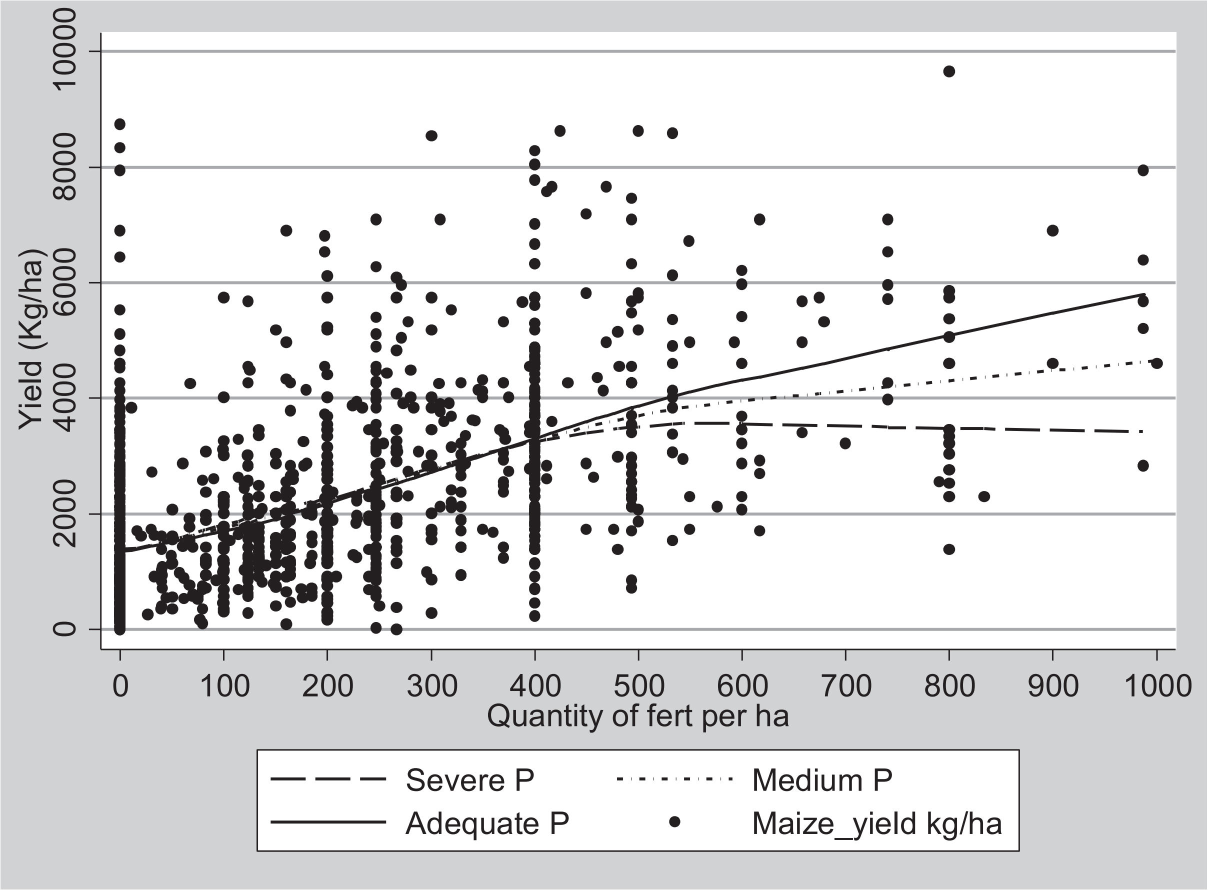


Figure 10: Maize yield by fertiliser application rate and soils P status
Source: Authors' computation

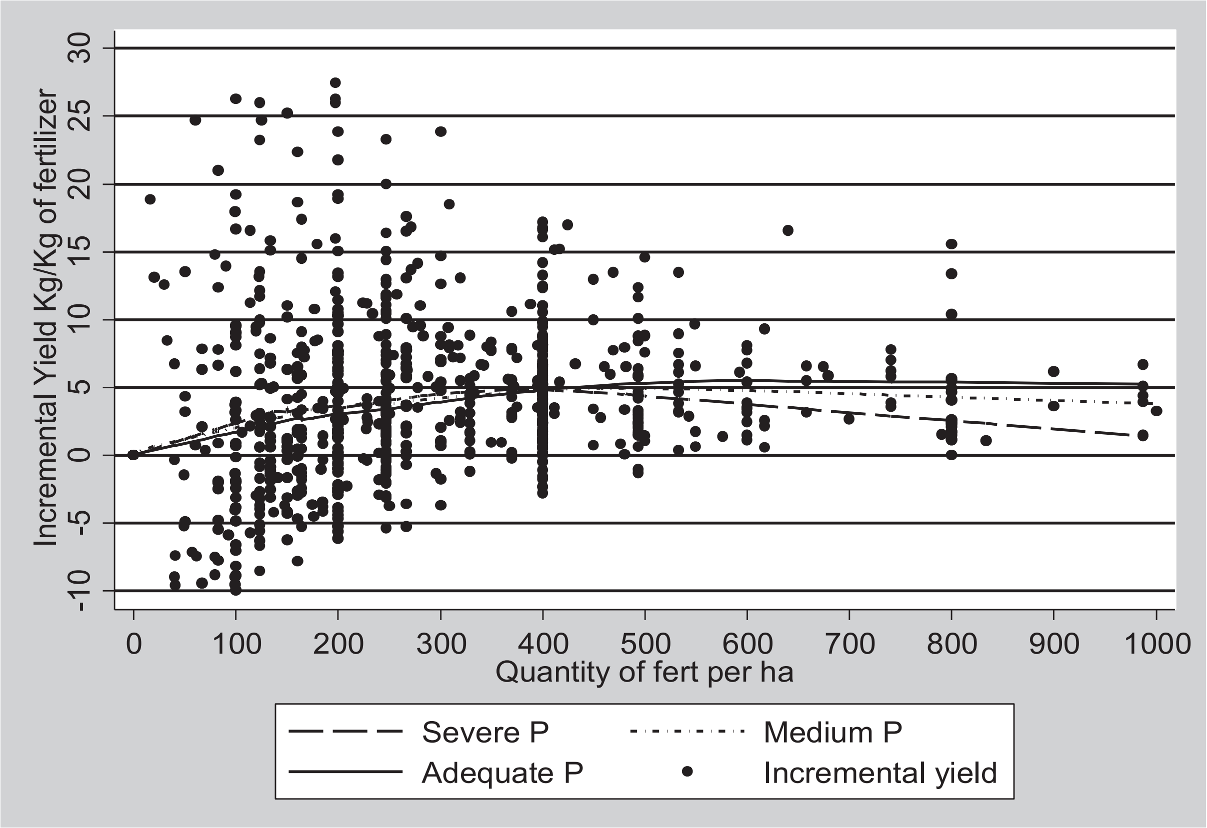


Figure 11: Incremental maize yield by fertiliser application rates
Source: Authors' computation

The trend is similar for maize net returns per hectare (computed as gross value of maize production less fertiliser costs per ha). In general, with additional application of fertiliser, the net returns decline a bit faster in severe deficiency phosphorous soils than in medium and adequate phosphorous soils. For example, in severe deficiency phosphorous soils, fertiliser application rates beyond 350kg result in a decline in net revenue as compared to about 500kg/ha in medium phosphorous soils, and more than 600kg/ha in adequate phosphorous soils. This is mainly due to the yield response to additional fertiliser which is greater in adequate phosphorous soils, followed by medium phosphorous soils, and lastly severe deficiency phosphorous soils (Figure12).

Economically there is a rate of fertiliser application, much lower than the agronomic maximum level, where no additional net benefit will result from applying more fertiliser. This rate is where the value to the farmer of any additional maize produced will be less than the cost of any additional fertiliser applied to the maize. This would be the level of fertiliser application which should be the maximum rate recommended for farmers. The amount of fertiliser actually applied is dependent to a large degree on the cost of the fertiliser and the value of the maize for the farmer. This amount may vary with

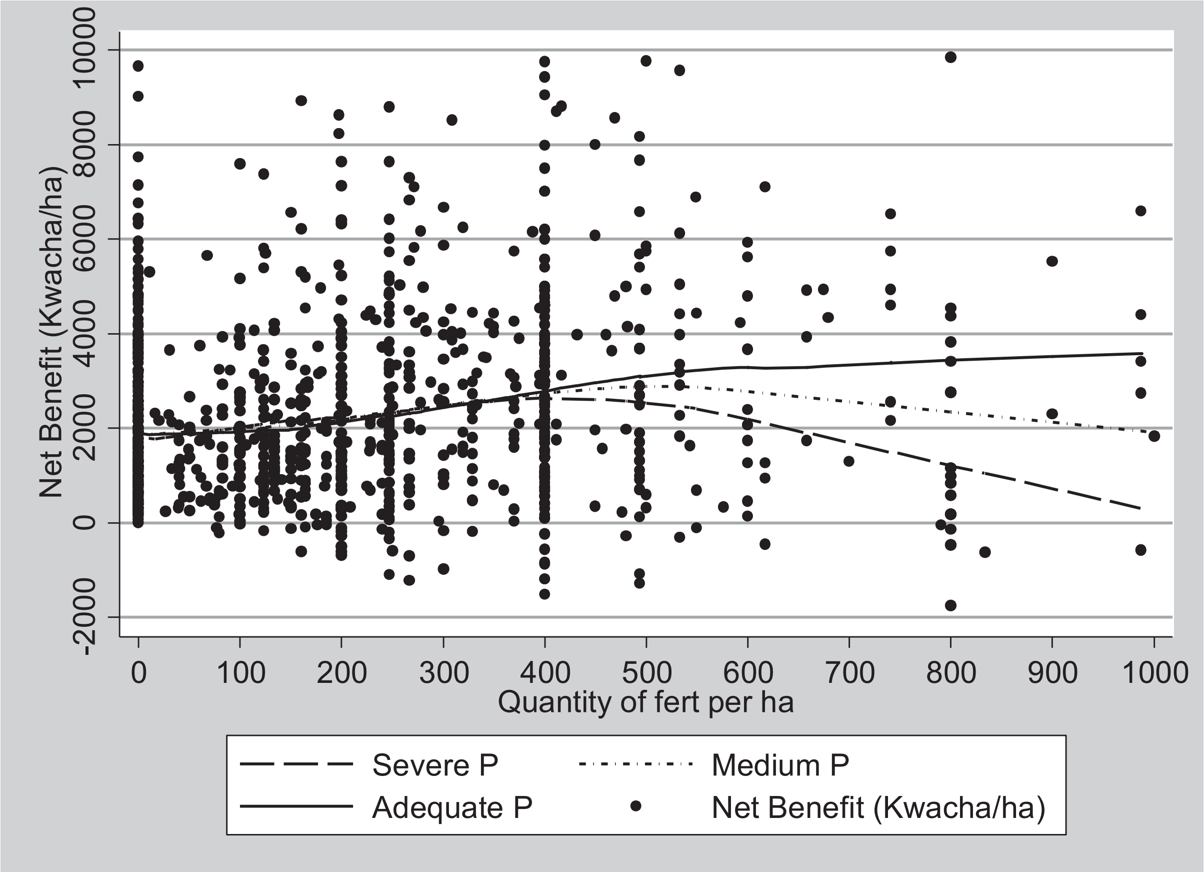


Figure 12: Net revenue per hectare by fertiliser application rate and soil P status
Source: Authors' computation

the recommended rate across the country. In Zambia, this has been a challenge because high fertiliser costs result in unprofitable use of fertiliser given the current low productivity. The Government of Zambia has responded to this by offering farmers prices above the market rate. Unfortunately this intervention is not optimal as the solution lies in addressing productivity issues through area-specific fertiliser recommendations. There is no doubt that high fertiliser prices, lower maize prices, and lower maize productivity, will result in lower levels of fertiliser use. There is an inverse relationship between the ratio of fertiliser to the price of maize, and the level of fertiliser use. Thus, if the fertiliser to maize price-ratio is increasing, the recommendation should be for farmers to use lower levels of fertiliser, and vice versa. This suggests that the blanket fertiliser application rate does not take into account the relative price ratio. This could be one of the reasons why fertiliser use levels are low in the country.

Moving towards area-specific fertiliser recommendations

It has been shown thus far that soil variability in terms of SOC, pH, and phosphorous is evident across the country. This variability, though not completely comprehensive for all soil nutrients, indicates that area-specific fertiliser recommendations are important for successful crop production. More importantly, they provide evidence that without soil analysis it is impossible to determine what the soil needs to be productive (Fery and Murphy, 2013). Farmers should use soil testing as a management practice for identifying nutrient variability across farm fields. This practice will ultimately guide decisions about soil fertility programmes that are responsive to crop needs, and will ensure that crops grow uniformly, whilst simultaneously assuring that all monies channelled towards fertiliser support are utilised in an efficient manner. We argue that soil testing may be the missing link in Zambian agriculture, particularly for smallholder farmers.

The challenge in soil testing for smallholder farmers is to guarantee that the process is agronomically sound. It should be noted that soil testing comprises various sampling procedures including: packaging and labelling, soil analysis, interpretation, and management recommendations. To be effective, extension officers and, ultimately, farmers will require training in the testing aspects to warrant scientific soundness of the soil test results and recommendations arising therefrom. Another challenge to area-specific recommendation is the prohibitive costs that may be associated with soil testing. Generally, farmers, whether large or small, need cheaper, reliable soil testing facilities that can give them results in a quick and efficient manner. They should not have to use distant central laboratories (e.g. Lusaka), which have a long waiting time before test results and recommendations are recieved.

The hindrances outlined above can be overcome by applying current on-site soil testing technologies such as: infra-red spectroscopy, and mobile soil analyser. These technologies and associated soil testing kits can be located at district level where logistics for travel are simpler. Extension workers can be trained to instruct farmers on how to take a soil sample that conforms to the science of soil sampling and testing. These samples can then be brought to the district office where farmers can wait for them to be analysed, and receive the recommendations upon completion of the analysis. Some of the analysis in these newer technologies can take 2 to 24 hours, this represents a realistic time frame for farmers to wait. Notably, this approach is already being piloted in certain developing countries such as Kenya and Rwanda (Agriculture for impact: Growing opportunities for Africa's development, 2015). Therefore, apart from central laboratory facilities, mobile testing kits and facilities can be used to make testing facilities more accessible across the country. This approach is being piloted by a project in Zambia, at ZARI and UNZA, sponsored by the Japanese International Cooperation Agency (JICA). Under this project, mobile soil testing kits are being stationed in various provinces and districts to make them easily accessible to farmers, thus eliminating long travel distances to testing facilities.

Mobile soil testing enhances the feasibility of area-specific fertiliser blending and production based on the general soil nutrient status of a given area. Soil testing may be tied to the government supported fertiliser support programmes by making soil testing a precondition to accessing the fertiliser as farmer input support. This may guarantee that fertilisers accessed and applied by farmers are area specific. This approach may also be supported by other projects that support conservation farming where farmers accessing support for CA practices can test their soils. This soil testing may in the long run allow for monitoring how the soil status is changing with use of inputs and other practices such as CA.

Conclusion and Recommendations

This study has demonstrated that soil variation exists across the country. We observed this in all the mapped soil properties with ranges of 2.7 to 7.8 for soil pH, 0.08% to 10.1% for SOC and 1.0 ppm to 333.6 ppm for soil phosphorous. These values belong to different classes in terms of acidity, levels of adequacy, and deficiency. This indicates that blanket fertiliser recommendations or even liming may not be well suited across the entire country.

In view of the findings of this study, we make the following recommendations;

1. The promotion of soil testing by farmers: It should be noted that yield and ultimately economic return are optimised when fertiliser is applied according to soil conditions. Therefore, soil testing by farmers should be recommended. This can be done either by setting up soil testing centres or using mobile soil testing kits. Central to the success of this programme is proper soil sampling. This entails that the soil testing facilities should also provide training to farmers and extension staff on the correct procedures and/or methods of soil sampling. The current cost of mobile testing kits ranges from US$20 to around US$50 for pH, N, P, and K besides reagents needed for their routine operation and maintenance. It should be noted that average cost of laboratory soil testing in Zambia is K255 (US$26) per sample. This may be too expensive for most smallholder farmers who have been relying mainly on government-subsidised fertiliser support.
2. Given the extent of financial allocation to FISP, the effectiveness of the programme can be enhanced if some of the resources can be channelled to soil testing and map production. The soil testing can be done using mobile kits by extension staff with a few samples taken for confirmatory tests in the laboratory. Some of the resources can also be channelled to research centres such as ZARI, and universities such as UNZA, to enable them to provide affordable soil testing services to farmers within their locality. It would be important that the soil testing information and results are geocoded and collated for use in updating and generating soil maps at various levels.

3. The establishment of farmer demonstration plots: In order for farmers to understand the need for soil testing and the results of location-specific fertiliser recommendation, there is need to set up demonstration plots in various locations. To ensure effective learning, the demonstration plots can be set up as farmer field schools.
4. Regular generation and updating of soil maps: Since soil properties change with time, there is need for regular updating of existing maps as well as generation of new maps. TGeostatistical approaches as demonstrated in this paper and soil legacy data coupled with appropriate remote sensing toosl can be used to generate new maps. These maps should be produced at national as well as district level to ensure that even soil variation at this larger scale is addressed.

Endnotes

1 AEZ I covers the country’s major valleys: Gwembe, Lunsemfwa, and Luangwa, and the southern parts of Western and Southern provinces that are drought-prone. It is characterised by low rainfall (< 800 mm/year) and a short, hot growing season. AEZ II is the medium rainfall area (800-1,000 mm/year) and is divided into AEZ IIa and IIb. AEZ IIa has higher rainfall with a longer crop growing period. The highest maize producing areas in Zambia are found in this region. AEZ IIb mainly has coarse sandy soils and is able to support some agriculture production. AEZ III, with rainfall of 1,000-1,500 mm/year occupies 41% of the country covering Northern, Luapula, Copperbelt and, North-western provinces, and parts of Central Province.

References

Agriculture for impact: Growing opportunities for Africa’s development. (2015). Soil Testing. Available at: http://ag4impact.org/sid/ecological-intensification/precision-agriculture/soil-testing/. Date accessed: April 10, 2016.

Bray, R. H. and L. T. Kurz. (1945). Determination of total organic and available forms of Phosphorus in Soils. *Soil Science*, 59(1): 39-45.

Bolstad, P. 2009. GIS Fundamentals: A first Text on Geographical Information Systems, 4th Edition., Minnesota: White Bear Lake.

Burke, J.W, F., S. Kabwe, and T.S.Jayne. (2015). *Understanding fertilizer effectiveness and adoption in Zambia*. Paper presented at 29th International Conference of Agricultural Economists, Milan. International Association of Agricultural Economists (IAAE).

Burrough, P.A. and R. A. McDonnell. (2004). Principles of Geographical Information Systems. New York: Oxford University Press.

Cakmak, I. (2002). Plant nutrition research: Priorities to meet human needs for food in sustainable ways. *Plant and Soil*, 247: 3–24.

Chapoto, A., and C. Ragasa. (2013). Moving in the Right Direction? Maize

Productivity and Fertiliser Use and Use Intensity in Ghana. IFPRI. Discussion Paper 1314. Washington, DC: International Food Policy Research Institute.

Central Statistical Office, Ministry of Agriculture and Livestock and Indaba Agricultural Policy Research Institute, (CSO/MAL/IAPRI). 2012. (RALS) Rural Agricultural Livelihoods Survey Data. Lusaka, Zambia: CSO/MAL/IAPRI.

Dufey, J., L. Bock, and G. Colinet. (2010). Effect of parent material and land use on soil phosphorus forms in southern Belgium. Proceeding of the World Congress of Soil Science, Soil Solutions for a changing world. August 1-6, Brisbane Australia, Published on DVD.

Erestein, O. (2003). Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. *Agriculture, Ecosystems and Environment*, 100(1):17-37.

Eswaran, H., R. Almaraz, E. van den Berg, and P. Reich. (1997). An assessment of the soil resources of Africa in relation to productivity. *Geoderma*, 77(1):1-18.

Ezui, K.S., C. K. Daudu, A. Mando, M. T. Kudi, A. C. Odunze, J.O. Adeosun, I. Y. Amapu, B. Tarfa, I. Sambo, I. Bello, and C. Dangbegnon. (2010). Informed site-specific fertiliser recommendation for upland rice production in northern Guinea savannah of Nigeria. In *Proceedings from the Second Africa Rice Congress Bamako, Mali, Innovation and Partnerships to realize Africa's Rice Potential*, March 22-26, 2010. Available at: http://www. africaricecenter. org/warda/arc. htm. Date accessed: March 2, 2016

FAO (Food and Agriculture Organisation of the United Nations). (2005). Fertiliser Use by Crop in Ghana. Rome: Food and Agriculture Organisation. Available at :ftp://ftp.fao.org/agl/agll/docs/fertuseghana.pdf. Accessed May 28, 2015.

Fery, M. and E. Murphy. (2013). A guide to collecting soil samples for farms and gardens. Available at http://catalog.extension.oregonstate.edu/ec628. Date accessed: April 10, 2016

Grant, C.A, D. N. Flaten, D. J. Tomasiewicz, S.C. Sheppard, and A. M. Johnston. (2001). The Importance of Early Season Phosphorus Nutrition. C*anadian Journal of Plant Science*. 81 (2): 211–224.

Guo, Z., J. Koo, and S. Wood. (2009). Fertiliser Profitability in East Africa: A Spatially Explicit Policy Analysis. In 2009 *Conference*, August 16–22, 2009, Beijing, *China* (No. 51710).

Havlin, J.L, S. L. Tisdale, W.L. Nelson, and J. D. Beaton. (2004). Soil Fertility and Fertilisers: An Introduction to Nutrient Management (7th Edition). USA: Pearson.

Hinsinger, P. (2001). Bioavailability of soil inorganic P in the rhizosphere as affected by root induced chemical changes: a review. *Plant and Soil*, 237(2): 173 – 195.

JAICAF. (2008). Agriculture and Forestry Issues in Zambia; Present situation and issues for development. Japan Association for International Collaboration of Agriculture and Forestry.

Johnston, K., J. M. VerHoef, K. Krivoruchko, and N. Lucas. (2001). Using ArcGIS geostatistical analyst (Vol 380). Redlands, CA: ESRI press.

Kelly, V. A., M. Morris, R. J. Kopicki, and D. Byerlee, D. (2007). Fertilizer use in African agriculture: lessons learned and good practice guidelines. Washington, DC: World Bank.

Lungu, O.I. (1987). Review of Soil Fertility and Fertiliser Research in Zambia. In *Proceedings for East and Southeast African Fertiliser Management and Evaluation Network Workshop*, 231-256, May 27-29, Nairobi, Kenya.

Lungu, O.I. and V. R. N. Chinene. (1993). Cropping and soil management systems and their effects on soil productivity in Zambia. A review Ecology and Development Paper No:5, Agricultural University of Norway, Aas, Norway.

Lungu, O.I. and R. F. Dynoodt. (2008). Acidification from long-term use of urea and its effect on selected soil properties. *African Journal of Food Agriculture, Nutrition and Development* (AJFAND), 8 (1): 63-76.

Mambo, A. and L. K. Phiri. 2004. Soil acidity map of Zambia. Zambia Agriculture Research Institute. Lusaka, Zambia.

Malama, C.N. (2001). Evaluating the agronomic potential of *Tithoniadiversifolia* prunings in the acid soils of northern Zambia. In *Proceedings of the Seventh Eastern and Southern Africa Regional Maize Conference, Harare, Zimbabwe*, 1115, 372-376).

McNeal, E.O. (1982). Soil pH Measurements. In *Methods of Soil Analysis Part 2*. (Edited by Keeney, D.R., R. H. Miller, and A. L. Page) Soil Science Society of America, Inc. USA, 203-209.

McPhillips, J.K. and A. J. Prior. (1979). Introducing the Lima. Department of Agriculture, Lusaka, Zambia.

McPhillips, J.K. (1983). The Development of Fertiliser Recommendations for Maize with particular reference to the high rainfall areas of Northern Zambia. In *Proceedings of Seminar on Soil Productivity Research in High Rainfall Areas of Zambia, Lusaka, Zambia* 219-229, February 8-10, Occasional Paper 6, H. Svads (Ed.), Agric. Univ., Norway.

Ministry of Agriculture. (1991). Soil Survey Section, National Soil map of Zambia.

Mwale, W. (1988). Review of agronomic work on open-pollinated maize: 1960 to 1987. Department of Agriculture, Mount Makulu Research Station, Zambia.

Ndlanga Mandla, G. M. (1998). The performance of (zea mays L.) cultivars under different fertilizer rates and soil types in two agro-ecological zones in Swaziland. Master's thesis, University of Zambia.

Omnia Fertilizers. 2013. Omnia Fertilizer product list, Lusaka, Zambia. Available at: http://www.proteachemicals.co.za/pebble.asp?relid=1363. Date accessed: March 2, 2016

Page, A.L., R. H. Miller, and D. R. Keeney (Eds). (1982). *Methods of Soil Analysis. Part 2. Chemical and Micro-biological Properties*. Second Edition. American Society of Agronomy, 9: 1159.

Rosenstock, T.S., D. Liptzin, J. Six, and T. P. Tomich. (2013). Nitrogen fertilizer use in California: Assessing the data, trends and a way forward. *California Agriculture*, 67(1): 68-79.

Russell, A.E., C. A. Cambardella, D. A. Laird, D. B. Jaynes, and D. W. Meek. (2009). Nitrogen fertilizer effects on soil carbon balances in Midwestern U.S. agricultural systems. *Ecological Applications*, 19 (5): 1102–1113.

Sanchez P.A., and G. Uehard. (1980). Management considerations for acid soils with high Phosphorus fixation capacity. In *The role of phosphorus in agriculture*. American Society of Agronomy, Madison, Wisconsin.

Shitumbanuma, V. (2012). Analyses of crop trials under *Faidherbia albida*. Conservation Farming Unit Report, University of Zambia.

Siame, J., R. W. Willey, and S. Morse. (1998). The response of maize/*Phaeolus* intercropping to applied nitrogen levels on oxisols in northern Zambia. *Field Crops Research*, 55(1), 73-81.

Snapp, S.S., M. J. Blackie, and C. Donovan. (2003). Realigning research and extension to focus on farmers' constraints and opportunities. *Food Policy*, 28 (4): 349–363.

Tilman, D., K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky. (2002). Agricultural sustainability and intensive production practices. *Nature*, 418 (6898): 671-677.

Umar, B.B, J. B. Aune, and O. I. Lungu. (2013). Effects of *Faidherbia albida* on the fertility of soil in smallholder conservation agriculture systems in eastern and southern Zambia. *African Journal of Agricultural Research*, 8(2): 173-183.

Wasonga, C.J., D. O. Sigunga, and A. O. Musandu. (2008). Phosphorus Requirements by Maize Varieties in Different Soil Types of Western Kenya. *African Crop Science Journal*, 16 (2): 161-173.

World Reference Base for Soil Resources (WRB). (2006). A framework for international classification, correlation and communication. World Soil Resources Report No. 103. FAO, ISRIC, International Union of Soil Sciences.

Xu, Z., William J. Burke, T. S. Jayne, and J. Govereh. (2009a). Do Input Subsidy Programs 'Crowd In' or 'Crowd Out' Commercial Market Development?

Modeling Fertilizer Demand in a Two-Channel Marketing System. *Agricultural Economics* 40.1: 79–94.

Xu, Z., Z. Guan, T. S. Jayne, and B. Black. (2009b). Factors Influencing the Profitability of Fertilizer Use on Maize in Zambia. *Agricultural Economics* 40.4: 437– 446.

Yerokun, O. (2008). Chemical characteristics of phosphorus in some representative benchmark soils of Zambia. *Geoderma*, 147 (1): 63-68.

Zambian Fertilizers. (2013). Fertilizer guide. Lusaka, Zambia. Available at http://www.zambianfertilizers.com/. Date accessed: April 10, 2016

Zamseed. (1993). Maize production guide. Zambia Seed Company Limited, Lusaka, Zambia.