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Soil Mapping, Fertilizer Application, and Maize Yield: A Spatial Econometric Approach

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Contents

Abstract

Despite the increasing availability of precision agriculture technology, most farmers in developing countries are still practicing farming with limited reliable information on soil characteristics. Using a unique geo-referenced dataset from the Democratic Republic of Congo, this article provides empirical insights on the spatial effects of fertilizer application on maize yield while estimating the size and direction of spatial spillover effects (direct and indirect effects) from leaching and runoff. Three fertilizer application scenarios are examined: i) homogeneous fertilizer application, ii) site-specific or heterogeneous, and iii) site-specific with spillover effects. Maize yield response is then assessed for the three scenarios. We found significantly higher maize yields under site-specific application (8.4 tons/ha) compared to homogeneous application (2.0 tons/ha). Our findings also provide evidence of spillover effects as the average maize yield is reduced by 1.9 tons/ha when spatial spillovers are accounted for. As anticipated, farmers' profitability with homogeneous fertilizer application is lower in comparison to site-specific application. Furthermore, excluding areas with potentially lower gross profit margins results in a 35.6 percent increase in gross profit (site-specific), and a 22.7 percent increase (site-specific with spillovers).

Fertilizer Application and Maize Yield: A Spatial Econometric Approachs

John M. Ulimwengu and Aziza Kibonge

1. INTRODUCTION

The efficient use of inputs is a pathway to the transformation of Africa's agricultural sector and the attainment of sustainable growth. Evidence from Asia and Latin America shows that agricultural productivity was a determining factor in these regions' structural transformation and subsequent economic growth (Crawford et al. 2006). Countries in these two regions experienced substantial increases in agricultural productivity resulting from the use of yield-enhancing improved agricultural inputs, including fertilizers (Johnson et al. 2003, Sheahan 2017). While some African countries have achieved growth in fertilizer use per unit of cultivated land, the average fertilizer consumption rate in Africa is still significantly lower (25 kg/ha) than the average consumption in all other parts of the world (178 kg/ha in Asia, 135 kg/ha in the Americas, 77 kg/ha in Europe) (FAO, 2020).

Nitrogen (N) in particular, is a low-cost option that has been widely used in agriculture for several decades. Globally, the doubling of crop yields is linked to a sevenfold increase in Nitrogen fertilizer usage (Han et al. 2016, Ahmed 2017). However, the excessive use of Nitrogen fertilizers beyond a certain threshold is associated with low Nitrogen use efficiency and offers no yield benefits (Ahmed 2007). For most plant species, Nitrogen use efficiency varies from 30-50 percent, while the remaining 50-70 percent Nitrogen is either utilized by soil micro-organisms, lost through leaching, and/or volatilized to nitrous oxide (Wuebbles 2009, Ahmed 2007). Furthermore, the excessive use of Nitrogen has been shown to pose some serious threats to environmental and human health (Ahmed 2007).

While high fertilizer application can potentially lead to pollution and water contamination without any yield improvements, inadequate fertilizer application will most likely result in poor yields and reduced profitability. This is even more relevant for farmers in Africa who often rely on national nutrient application recommendations that do not reflect local cropping systems, climatic conditions, and variability in soil content.

Precision Agriculture (PA) practices therefore have the potential to transform African agriculture while avoiding the negative effects associated with intensive application of nutrients. Site-specific nutrient application for example can play a significant role in achieving food security in Africa given its potential to increase yields by enabling farmers to match fertilizer application to site-specific conditions. Although there is evidence suggesting that precision agriculture practices lead to increased farm profitability by improving crop production, there are limited success stories of PA adoption in Africa (Larson and Robert 1991; Zhang, Wang, and Wang 2002).

This paper examines the correlation between maize yield and nutrient application under homogeneous fertilizer application (based on national recommendations without accounting for site-specific soil characteristics), and PA-guided fertilizer application (site-specific or heterogeneous application, resulting from soil analysis). As nutrient application in one given area may result in no yield improvements but instead lead to increased nutrient supply in neighboring areas due to downslope leaching and runoff, the effects of nutrient application on maize yields, and the associated spillover effects are analyzed.

This study's objectives are twofold: (i) to examine the effects of fertilizer application on crop yields and farmers' profitability under 'homogeneous' application and site-specific application; and (ii) to estimate direct and indirect effects of fertilizer application by accounting for area-to-area spillovers in fertilizer application (via aerial drift or downslope leaching and run-off)

The paper is organized as follows. In the next section, a brief background is presented on the profitability of site-specific fertilizer management. An overview of the methodology and data is then reviewed, followed by a discussion of the results. Finally, concluding remarks are provided.

2. Precision Agriculture and Farm Profitability

Profitability is the principal determinant for adoption of new technologies in agriculture. However, the profitability of any given agricultural technology may differ greatly for several reasons including variability across regions and crops. Likewise, differences in climate and soil characteristics can lead to variations in crop productivity and the long-term profitability of adopting new agricultural technologies such as Precision Agriculture (PA).

PA is a spatial management approach that can lead to the more appropriate use of inputs which benefits the profitability of the enterprise and natural resource management (Leonard 2014). Although PA and other management technologies have been increasingly used in the last decades, earlier reviews had raised questions about their profitability while more recent studies have come to the same conclusion (Swinton and Lowenberg-DeBoer 1998; Lowenberg-DeBoer 2018; Lowenberg and Erickson, 2019).

Precision agriculture is likely to be adopted as variable rate technologies have been shown to provide higher economic benefits (Bullock, et al. 2002, Isik & Khanna, Liu et al. 2006; Finger et al. 2019). Earlier studies reported that adoption of PA depends on several factors including the interactions between farm size, cost of PA equipment and the yield increase required to offset the costs (Godwin et al. 2003; Griffin et al. 2004). Van Evert et al. (2017) found that PA application leads to a reduction in nitrogenous fertilizer use and increased profits. Farmers may incur costs from PA adoption but farm profitability also increases.

Studies have found that variable rate nutrient application has the potential to positively affect farm incomes by increasing crop yields in comparison to uniform nutrient application. In some cases, the revenue was shown to increase by 9.7 Euros/ha when fertilizer was applied before seeding at a fixed rate, and by more than 24.7 Euros/ha when fertilizer was only applied in-season (Raun, et al. 2001, and Raun et al. 2002). Others found that variable rate nutrient application based on site-specific management zones led to an increase of 25.6 to 38.6 Euros/ha in net returns (Koch et al. 2004) in comparison to uniform nutrient application.

In addition, variable rate technologies can lead to increased returns derived mainly from the reduced use of fertilizer quantities as they only cover site-specific nutrient needs, thereby reducing costs of fertilizer utilized (Babckock and Pautsch 1998; Godwin et al. 2002; Mamo et al. 2003; Balafoutis, A. et al. 2017). PA has the potential to substantially improve yields with optimal input use for both small-scale and commercial agro-systems. Indeed, it is expected that under PA, farming inputs can be used more effectively and efficiently with subsequent improvements in yields and profits while minimizing potential environmental damage from homogeneous application. Despite these benefits, there is limited evidence of PA adoption in African farming (Jensen et al. 2012; Takacs-Gyorgy et al. 2013; Ncube B. et al. 2018).

In Sub-Saharan Africa, the considerable variability observed in soil quality or properties largely contributes to variations across space and time in crop productivity and profitability following fertilizer application, especially under rain-fed agriculture (Tittonel et al. 2008; Naab et al. 2015). Farmers in these countries have largely relied on either observed past crop yields, or on national government recommendations for fertilizer application. However, these recommendations are made at high levels of aggregation and do not take variability in soil and weather patterns into account, and so fail to meet the needs of smallholder farmers (Tittonel et al. 2008; Dufflo et al. 2008).

Estimates on the profitability of PA also depend on the model specifications used, with all spatial models consistently indicating profitability, whereas the non-spatial models do not. This suggests that yield monitors are inherently spatially correlated (Anselin et al. 2004) and consequently spatial statistical methods should be used to obtain reliable estimates of economic returns (Bullock and Lowenberg, 2007). In addition, spatial spillover effects have been shown to matter and should therefore be accounted for to avoid biased estimates. Yang (2019) examined spatial spillover effects from intensive farming on dairy yields and found that nutrient spillover via runoff and aerial drift causes substantial effects beyond fenced boundaries, even when forested areas were fenced off for conservation and livestock access prevented.

This paper aims to fill the gaps in the literature as farmers' profitability is evaluated under both variable rate and uniform nutrient application (based on national recommendations). This is the first attempt at using a spatial model to estimate maize yields and farm profitability while taking the variability across regions into account. In addition, this paper examines the effects of spatial spillovers from nutrient application on farmers' profitability.

3. Methodology

We use an extension of the model originally developed by Anselin et al. (2004) to account for the effects of spatial autocorrelation from spillovers, externalities or other imperfections in models and measurements that require a spatial specification. The modified model also accounts for area-to-area spillovers in fertilizer application via aerial drift or downslope leaching and run-off. Since there exists a linear relationship between agricultural intensity and cumulative levels of Nitrogen, Phosphorus, Uranium and Cadmium in neighboring soils (Didham, 2015), it may be inferred that fertilizer applied in one area of the farm can find its way into another area of the same farm because of spillover. As pointed out by Didham (2015), this phenomenon can render the production system completely inefficient, while farming profits and environmental damage would become unpredictable. Empirically, ignoring nutrient spillover will likely produce biased estimates of the impact of fertilizer application on crop yield. Moreover, the model specification used in this study disentangles marginal effects of fertilizer application into direct (from application on a given area), and indirect (from spillover from neighboring areas) effects.

Empirically, a spatial Durbin model (SDM) which includes spatial dependence in both the explanatory variables and the errors is implemented as specified in equation (1):

$$(1) \quad y = \alpha i_n + \rho W y + X\beta + WX\theta + \varepsilon ,$$

where *y* is a vector *(n x 1)* of observations on the dependent variable, *X* a *(n x k)* matrix of observations on the explanatory variables, i_n is a vector of ones, α is the associated intercept parameter, $\varepsilon \sim N(0, \sigma^2 I_n)$, and *W* is a *(n x n)* spatial weights matrix where each row contains non-zero elements for the columns corresponding to inverse distance to "neighbors".

Equation (1) can be rewritten as:

$$(2) \quad y = (I - \rho W)^{-1}[\alpha i_n + X\beta + WX\theta + \varepsilon] ,$$

Hence, following LeSage and Pace (2009), the partial derivatives of y with respect to a change in the r[th] variable x^r from *X* is given by equation (3):

$$(3) \quad \frac{\partial y}{\partial x_r'} = (I - \rho W)^{-1}[I_n \beta_r + W\theta_r]$$

The partial derivatives are an *(n x n)* matrix rather than the typical scalar expression β_r from ordinary least squares (OLS) estimation. As pointed by LeSage and Pace (2014), this arises because a change in a single observation x_{ir} can influence all observations of the vector y_j, *j=1,..,n*. The own-plot or direct response is given by $\partial y_j / \partial x_{ir}$ which are elements on the diagonal of the matrix in equation (3), while the cross-partial derivatives $\partial y_j / \partial x_{ir}$ with $j \neq i$ represent indirect or spillover responses, and are on the off-diagonal elements of the matrix in equation (3).

LeSage and Pace (2009) argue that spillovers in the context of cross-sectional spatial regression models should be interpreted as comparative static changes that will arise in the dependent variable as the relationship under study moves to a new steady-state equilibrium. This is because cross-sectional observations could be viewed as "reflecting a (comparative static) slice at one point in time of a long-run steady-state equilibrium relationship, and the partial derivatives viewed as reflecting a comparative static analysis of changes that represent new steady-state relationships that would arise" (LeSage 2014, p.18).

Following Anselin et al. (2004), expected maximum profit can be expressed as:

$$(4) \quad \text{Max } E[\pi] = \sum_{i=1}^{n} \text{Area}_i * E\left[P_c * y(x_{ik}) - \sum_{k=1}^{K} r_k * x_{ik}\right],$$

where *E* is an expectation operator; Π is the total net returns over Nitrogen fertilizer ($ ha^{-1}); is the proportion of landscape area *i*; P_c = price of maize ($kg^{-1}); x_{ik} is the quantity of nutrient k applied in area *i;* and rk is the price of nutrient k ($kg^{-1}).

The yield (y) is modeled as a spatial Durbin Error model with interaction terms.

4. Study Area and Data Collection

In 2014, the government of the Democratic Republic of Congo (DRC) launched the first agro-industrial park called *Parc Agro-industriel de Bukanga-Lonzo* located 250 km east of the capital city of Kinshasa. The park site covers an area of 80,000 ha with approximately 70 percent (54,707 ha) of this land suitable for farming activities. The PA project started with soil and classification analysis conducted over 10,575 ha (see Map 1), of which 5,721.5 ha were allocated to maize production. Soil samples were tested to determine the texture, color, structure, reaction of the soil as well as the relationship and thickness of the different soil horizons (Summary Soil Analysis, 2015). A summary of the main findings is presented in Table 1 and shows a heterogeneous site with four types of soil (Cartref, Clovelly, Fernwood, and Constantia).

Each type exhibits different levels of depth and clay content, both factors which usually play an important role in water storage capacity[1]. The most dominant soil type is Constantia which consists of an Orthic A-horizon, followed by an E-horizon, and a third horizon consisting of a yellow brown apeda. The remaining soil types were far less represented (Ulimwengu and Kibonge 2017). The E-horizon formed is due to water that drains laterally out of the horizon and is therefore highly leached. The thickness of the E-horizon has an impact on the soil potential mainly because this horizon is highly leached and has problems of oxygen deficiencies. The analysis indicates that the thicker white E-horizons are located on the flatter topography while the thinner white E-horizons are to be found more on the slopes. In the flatter areas, water tends to penetrate deeper before it starts to drain laterally whereas on the slopes, water starts to drain laterally earlier because of slope gradient leading to a thinner white E-horizon.

Parameter	Soil	Normal Range	Recommendations
pH	4.4 Kcl (low)	5.5-6.5 Kcl	Indication of highly leached soils, therefore, Dolomitic lime should be used to correct the pH in the soil.
Exchangeable acids	Between 2.33 Cmol+/kg and 0.3 Cmol+/kg (very high)	0 Cmol+/kg	High exchangeable acids level is very toxic to plants and plant roots.
Magnesium (Mg)	Between 8 mg/kg and 6 mg/kg	100-120 mg/kg	Highly leached soils cannot physically retain enough Mg on the clay complex. The deficiency in Mg can be corrected by using Dolomitic lime.
Acid saturation	Between 42% and 51%	0 - 7%	Very high and may result in poor root development and stunted growth.
Potassium (K)	12 mg/kg	70-90 g/kg	Deficiency can be corrected by using a K source like KCl (50) fertilizer, or by applying a greater amount of fertilizer blend that is high in K.
Calcium (Ca)	Between 51 mg/kg and 39 mg/kg	200-220 mg/kg	If the physical amount of Ca in the soil is corrected, the pH will also start to stabilize above 5 KCl. Deficiency in Ca can be corrected by using either Dolomitic and/or Calcitic lime.

Table 1. *Soil Characteristics for Phase I - 2014*

Source: AgriXcellence (2013)

Note: *'pH' is the potential in Hydrogen, 'Mg' is magnesium, 'K' is potassium, 'Ca' is calcium, 'KCl' is potassium chloride, 'mg' is milligrams, 'kg' is kilograms.*

Based on the soil and classification analysis, site-specific recommendations on nutrient application were formulated to optimize maize yields (Table 2). As shown in Table 2a, Fernwood soil type requires higher nutrient levels, therefore the homogeneous application of fertilizers across soil types is not recommended.

A thicker white E-horizon implies the need for additional nutrients (Table 2b). Highly leached soils cannot retain enough magnesium (Mg) in the clay complex. An increase in the soil organic matter is therefore necessary to reach the appropriate fertilizer mix (Calcium (Ca), Magnesium (Mg), Potassium (K) and Phosphate (P)) to satisfy the plants' needs for magnesium. Table 2c suggests that soils experiencing very high nitrate loss would need about 22-40 percent more of each nutrient (Calcium (Ca), Monoammonium phosphate (MAP33), Phosphate (P), Magnesium (Mg), Potassium (K) and Potassium chloride (KCl50)) in comparison to soils experiencing low nitrate loss. In Bukanga-Lonzo, farmers applied Diammonium phosphate (DAP[2]), which is an excellent source of Nitrogen (N) and Phosphate (P), in addition to Potassium chloride (KCl) 0-60 which contains 60 percent potassium fertilizer (K[3]).

1 Soil texture varies by depth, so does water-holding capacity. To determine water-holding capacity for the soil profile, the depth of each horizon is multiplied by the available water for that soil texture, and then the values for the different horizons are added together (Plant & Soil Sciences eLibrary).
2 DAP contains 18 percent N and 46 percent Phosphate
3 As Potassium Oxide, or K_2O, also known as potash, yielding 50 percent K

While farmers usually apply N-supplying fertilizers (urea) and other nutrients (Ca, Mg, P, KCl50, and MAP33), split application in top dressing should be considered as heavy rain may leach away some of the fertilizer during a very wet season. The amount of nutrients applied should also be slightly higher in the second and third applications than in the first (Table 2d). Maize production is often subject to waterlogging which inhibits its growth and reduces grain yield (Ren et al. 2014, Florio et al. 2014). Waterlogging decreases the activity of key Nitrogen metabolism enzymes and further reduces N-use efficiency (Florio et al. 2017). The restriction of root growth, induced by waterlogging, limits the absorption of Nitrogen fertilizer, disrupting its uptake, transportation, and distribution in each organ, eventually leading to a reduction in N-use efficiency (Ren et al. 2014). As shown in Table 2e, an average of 1,217.7 kg/ha of Ca, 654.6 kg/ha of MAP, 33,290.1 kg/ha of Phosphate, 238.2 kg/ha of Mg, 144.0 kg/ha of K, and 579.3 kg/ha of KCl50 are recommended when there is a risk of waterlogging.

Table 2a. *Average Recommended Fertilizers (kg/ha) by Soil Type*

Soil types	Ca	MAP33	Phosphate	Mg	K	KCl50
Cartref	88.1	48.9	20.6	17.3	10.9	40.0
Clovelly	926.2	490.5	236.8	184.9	109.9	491.8
Constantia	1103.4	620.4	264.9	218.8	136.7	531.8
Fernwood	1263.9	679.5	299.6	245.0	149.2	597.6

Table 2b. *Average Recommended Fertilizers (kg/ha) by the Thickness of White E-horizon*

	Ca	MAP33	Phosphate	Mg	K	KCl50
0 cm	1263.9	679.5	299.6	245.0	149.2	597.6
Between 1 and 7 cm	1038.1	598.1	250.7	205.8	132.2	504.8
8 or 9 cm	1072.8	621.8	258.0	212.0	136.7	520.1
At least 10 cm	1177.5	608.8	282.0	234.6	134.3	563.0

Table 2c. *Average Recommended Fertilizers (kg/ha) by Level of Nitrogen Loss due to Leaching*

	Ca	MAP33	Phosphate	Mg	K	KCl50
Very high	1260.6	686.5	302.4	249.0	151.1	602.5
High	1086.4	609.2	257.8	211.0	133.9	520.1
Average	942.0	534.6	224.2	185.5	117.9	450.9
Low	926.2	490.5	236.8	184.9	109.9	491.8

Table 2d. *Average Recommended Fertilizers (kg/ha) by Frequency of Top Dressing*

Stats/mean	Ca	MAP33	Phosphate	Mg	K	KCl50
1 time	926.2	490.5	236.8	184.9	109.9	491.8
2 times	1037.6	584.0	246.4	202.4	128.5	496.7
3 times	1260.6	686.5	302.4	249.0	151.1	602.5

Table 2e. *Average Recommended Fertilizers (kg/ha) by Risk of Water Logging*

Stats/mean	Ca	MAP33	Phosphate	Mg	K	KCl50
Yes	1217.7	654.6	290.1	238.2	144.0	579.3
No	1122.5	636.9	275.7	224.5	140.5	557.7
Average	1013.1	589.4	241.4	199.7	129.8	485.4

Source: Calculated by the author using data from AgriXcellence (2013)

5. Model Estimation and Results

Model selection

While controlling for top dressing and E-horizon thickness, we hypothesize that maize yield is a function of fertilizers (MAPP33 and KCl). Moreover, since there might be some correlation between fertilizer application and E-horizon thickness, interaction terms were also included in the model to explore the potential relationships among fertilizer application, E-horizon thickness, and yield response. The model is augmented with quadratic terms to capture the possibility that fertilizer may not affect maize yield linearly. The results of an OLS model which does not account for spatial correlation, a spatial error model (SEM), and a spatial Durbin model (SDM) with spatially lagged fertilizers are presented in Table3-5.

***Table 3.** Goodness of Fit and Spatial Correlation Test*

	OLS	SEM	SDM Robust
Sample	6381	6381	6381
Wald/P-value	47495.1***	9491.7 ***	37408.4 ***
F-Test/P-value	2793.8***	558.3 ***	1100.3 ***
R^2	0.89	0.59	0.85
Log Likelihood	-10348.7	-10071.2	-9774.7
Moran I	74.8***		
LM† for spatial error (Burridge)	4126.6 ***		
LM† for spatial error (Robust)	3952.8 ***		
LR Test (wX's=0)			280.7***

Note: *Significance is denoted as follows: ***=1% level; **=5% level, and *=10% level, respectively.*

Source: *Estimated by the author. †=Lagrange multiplier*

The Lagrange Multiplier (LM) tests reject the null hypothesis of no spatially lagged term and no spatial autocorrelated error. Results from Moran's I test confirm the existence of spatial autocorrelation while the Wald test for the spatially lagged variable confirms that SEM must be rejected in favor of SDM Robust (preferred model). The spatial autoregressive parameter *lambda* in the spatial error model and *rho* in the Durbin model are all significant which suggests that spatial autocorrelation exists. The spatial model is therefore more appropriate than the OLS model which does not account for spatial correlation. Moreover, the LR test on lagged independent variables suggest that spillover from fertilizer application is significantly impacting maize yield. Therefore, the robust SDM was selected as the preferred specification[4]. Indeed, in addition to accounting for the spatial lag correction and the spillover from other spots, the robust SDM also accounts for the spatial error correlation. The model fit improves when the robust SDM is used, as shown by an increase in the log likelihood (-10,348.7 to -9,774.7). Thus, maize yield may not only depend on the variables of the targeted area but also on the variables from areas surrounding the targeted area.

Kernel density (Appendix) and the descriptive statistics in Table 4 confirm the accuracy of our estimation strategy. The average yield (6.5 ton/ha) is the same across specifications except for SEM. Although OLS estimates accurately replicate maize yields, they are biased and non-efficient because of significant spatial autocorrelation and spillover. The shape of the Kernel density also suggests that the planting area is not homogeneous, therefore, uniform application of fertilizers is neither efficient nor profitable.

***Table 4.** Estimated Maize Yield*

	Obs.	Mean	Std. Dev.	Minimum	Maximum
Observed	6,381	6.5	3.6	1.4	12.1
OLS	6,381	6.5	3.3	2.2	11.9
SEM	6,381	8.4	3.1	4.4	13.0
SDM	6,381	6.5	3.4	1.5	12.3
SDM-Robust	6,381	6.5	3.4	1.5	12.3

4 Because it includes a spatial lag on the dependent variable and independent variables and is therefore suitable to capture externalities and spillovers arising from different sources (Anselin 1988).

Source: Estimated by the authors.

Results

The findings suggest that increased fertilizer use will ultimately increase maize yields, however, the results also confirm that maize yields are more likely to be affected by spillover of fertilizer applications. This is consistent with a recent study by Yang (2019) which examines how spatial spillover effects influence the relationship between dairy yields and intensive farming in New Zealand. Their results show significant positive spillover effects on dairy yields resulting from intensive input application.

The marginal effects of explanatory variables for all specifications are reported in Table 5. These effects were decomposed into direct, indirect, and total effects (see LeSage and Pace, 2009). While the direct effects measure the own impact of fertilizer application and soil characteristics, the indirect effects measure the impacts from neighboring areas. The coefficients on spatially lagged fertilizers (KCL, MAP33) are statistically significant (at 1% and 5% levels) which is an indication of fertilizer runoff. When this occurs, some areas will end up with more or less fertilizer (MAP33, KCL) with the potential to affect expected yields. The results also indicate that the effects of fertilizer on maize yield are dependent on the soil structure, especially the E-horizon thickness. Harris *et al.* (2010) argue that the water table depth in relation to E-horizon thickness affects the availability of Phosphate applied to crops, as well as the potential for lateral transport of the nutrient through sub-surface flow. This should therefore be accounted for when determining the level of fertilizer application rates, especially in poorly drained soils which contribute to Nitrogen losses.

Table 5. *Estimation Results*

	OLS		SEM		SDM-Robust	
	Coeff.	SE	Coeff.	SE	Coeff.	SE
A. Variables						
Top dressing (1 if applied, 0 if otherwise)	-0.73***	0.05	-0.59***	0.05	-0.53***	0.07
Total MAP33 (kg)	0.01	0.68	0.37	0.65	0.83**	0.33
Total MAP33 squared	-0.01	0.48	-0.37	0.46	-0.74***	0.23
Total KCl (kg)	2.75***	1.02	2.77***	0.97	2.61***	0.53
Total KCl (kg) squared	-2.17*	1.18	-2.09*	1.13	-1.90***	0.58
Interactions between thickness of white E-horizon and fertilizers						
E-horizon thickness of 0 cm						
Total MAP33 (kg)	-0.28	0.82	-0.72	0.78	-1.22***	0.37
Total MAP33 squared	0.15	0.59	0.63	0.56	1.06***	0.27
Total KCl (kg)	-20.09***	1.19	-19.08***	1.14	-18.10***	0.58
Total KCl (kg) squared	16.40***	1.42	15.50***	1.35	14.70***	0.67
E-horizon thickness between 0 and 7 cm						
Total MAP33 (kg)	-1.30	0.94	-1.45*	0.89	-1.65**	0.69
Total MAP33 squared	1.60**	0.66	1.80	0.63	1.95***	0.48
Total KCl (kg)	0.07	1.38	-0.65	1.32	-0.72	1.08
Total KCl (kg) squared	3.76**	1.61	3.65**	1.54	2.83**	1.28
E-horizon thickness >7 cm but <=9 cm (dropped for multicollinearity)						
E-horizon thickness >9 cm						
Total MAP33 (kg)	-0.21	0.94	-0.63	0.90	-1.04**	0.51
Total MAP33 squared	0.56	0.70	0.98	0.67	1.31***	0.41
Total KCl (kg)	-7.75***	1.41	-6.56***	1.35	-5.42***	0.90
Total KCl (kg) squared	4.52***	1.70	3.41***	1.62	2.33**	1.13
B. Spatially lagged variables						
Top dressing (1 if applied, 0 otherwise)					-0.08	2.17
Total MAP33 (kg)					97.26***	22.18
Total MAP33 squared					-72.90***	15.60

	OLS		SEM		SDM-Robust	
	Coeff.	SE	Coeff.	SE	Coeff.	SE
Total KCl (kg)					-99.95***	33.82
Total KCl (kg) squared					86.00**	40.80
E-horizon thickness of 0 cm						
Total MAP33 (kg)					-70.02**	27.59
Total MAP33 squared					38.30**	19.20
Total KCl (kg)					81.64**	40.48
Total KCl (kg) squared					-42.20	47.40
E-horizon thickness between 0 and 7 cm						
Total MAP33 (kg)					-65.41	41.99
Total MAP33 squared					40.90	30.00
Total KCl (kg)					18.70	71.10
Total KCl (kg) squared					39.20	83.90
E-horizon thickness >7 cm but <=9 cm (dropped for multicollinearity)						
E-horizon thickness >9 cm						
Total MAP33 (kg)					-98.89***	28.80
Total MAP33 squared					90.30***	21.90
Total KCl (kg)					96.44**	44.60
Total KCl (kg) squared					-114.50**	57.40
Intercept	8.35***	0.04	10.04*	5.25	3.22	2.61
Lambda (λ)			0.997***	0.003		
Rho (ρ)					0.468*	0.274

Note: Significance is denoted as follows: ***=1% level; **=5% level, and *=10% level, respectively.
Rho is the spatial autoregressive coefficient.

Source: Estimated by the authors.

Our findings confirm that top dressing and total KCl are significant determinants of maize yield across all models (OLS, SEM, and SDM-Robust). While total MAP33 is only significant in the SDM-Robust model, total KCl is significant across all models even when interacting with thickness of white E-horizon (0 cm, and >9 cm) which indicates that yield response to fertilizer application (MAP33 and KCl) varies with thickness of E-horizon.

Finally, the results suggest that the effect of fertilizer applications on maize yield is not linear regardless of soil structure. The quadratic terms included suggest that there is a minimum level of fertilizer required to increase maize yield. In other words, if fertilizer applications fall below the required minimum amount, the likelihood of increasing yields is very low. This might explain some of the reported disappointing maize yields despite application of fertilizers.

6. Profitability Simulations and Policy Implications

Three main scenarios were considered to estimate the gross profit margin for maize (revenue minus cost[5]): i) the 'homogeneous' application scenario which represents the case where the farmer has no detailed knowledge of soil characteristics. In this case, the choice of fertilizer and the quantity applied are based on national recommendations as stated by the DRC's Ministry of Agriculture which is 200 kg/ha of fertilizer for an expected yield of 2 tons/ha of maize; ii) the 'site-specific' application scenario where the farmer has access to detailed soil characteristics through precision agriculture technology that allows for better targeting of fertilizer application. This scenario is then split into two – with and without fertilizer spillover; iii) the last scenario is an improvement of the second scenario where the farmer trims out areas with low gross profit margins. Table 6 presents the summary of variables used in these simulations.

5 Here we only consider the cost for fertilizer and precision agriculture.

Table 6. Summary of Variables used in Simulations

Variables	Obs.	Mean	Std. Dev	Min.	Max.
Maize price (USD)	6,381	380.0	0.0	380.0	380.0
Homogeneous application					
Area (ha)	6,381	1.0	0.1	0.0	1.0
Yield per government recommendation (tons/ha)	6,381	2.0	0.0	2.0	2.0
Production (tons)	6,381	2.0	0.2	0.0	2.0
Revenue (USD)	6,381	742.2	80.5	0.2	755.1
MAP33 (tons)	6,381	200.0	0.0	200.0	200.0
KCl (tons)	6,381	200.0	0.0	200.0	200.0
MAP33 price (USD/kg)	6,381	1.6	0.0	1.6	1.6
KCl price (USD/kg)	6,381	1.6	0.0	1.6	1.6
Heterogeneous without spillovers					
Area (ha)	6,381	1.0	0.1	0.0	1.0
Yield per government recommendation (tons/ha)	6,381	8.4	3.1	4.4	13.0
Production (tons)	6,381	8.2	3.1	0.0	13.0
Revenue (USD)	6,381	3103.5	1188.8	0.8	4926.7
MAP33 (tons)	6,381	0.6	0.3	0.0	1.2
KCl (tons)	6,381	0.6	0.2	0.0	0.8
PA cost (USD/ha)	6,381	75.0	0.0	75.0	75.0
cost_h1	6,381	75.1	8.2	0.0	77.5
profit_h1	6,381	3028.4	1186.6	0.7	4849.2
Heterogeneous with spillovers					
Yield (tons/ha)	6,381	6.5	3.4	1.5	12.3
Production (tons)	6,381	6.3	3.4	0.0	12.2

Source: Calculated by the authors.

As expected, uniform fertilizer application is less profitable, especially if the expected yield is at the national recommended level (i.e., 2 tons/ha). Even when we double the yield (4 tons/ha), the profit margin per hectare is still way below that of site-specific application (Figure 2 in Appendix). Although national recommendations may lead to crop yield increases, our results suggest that subsequent increases can be achieved by adopting targeted approaches which address specific soil constraints, crop needs and efficient nutrient management. Failure to formulate fertilizer recommendations that take spatial heterogeneity into account will likely result in inefficient use of resources, thereby rendering farming unprofitable which is a disincentive for smallholder farmers.

Another interesting finding is related to the inclusion of spillover or fertilizer runoff. In the case of the study site (Bukanga-Lonzo), the average profit per hectare is higher in the presence of spillovers as nutrient application in one given area leads to increased nutrient supplies in neighboring areas. The results imply that farmers can still earn more per hectare by trimming out areas with low expected gross profits. Using the knowledge on soil characteristics from precision agriculture, we removed about 44 percent of planting areas that offered lower gross margin (below the average). The resulting precision targeting increases the gross profit margin per hectare by 35.6 percent for uniform application with spillovers and by 22.7 percent for variable application without spillovers.

Spatial dependence between neighboring areas implies that farmers should take spillovers into account when applying inputs such as fertilizer, as their application may not only affect the targeted areas but also neighboring areas.

In summary, these findings warrant consideration from policy makers not only in regard to formulation of fertilizer policy recommendations especially given the great spatial variability, but also in increasing uptake of PA technologies. In Africa, the efficient utilization of soil knowledge generated through PA practices has the potential to break the downward spiral of poverty and food insecurity. However, PA practices and their effectiveness in achieving improved yields and higher productivity would be limited without agricultural extension services, especially for smallholder farmers. It has been shown that farmers' education and access to information through extension services significantly influences PA adoption in African countries. Thus, expanding these services would allow easy access to research information, as well as better interpretation and delivery of PA recommendations to smallholder farmers.

7. Conclusion

We assess the effects of fertilizer application and farmers' profitability on maize yields while accounting for spatial spillovers resulting from leaching or runoff. Our findings suggest that site-specific fertilizer application is associated with improved yields and higher profit margins.

While the results indicate that increased fertilizer use is associated with increased maize yields, they also suggest that the likelihood of increasing maize yield is very low when fertilizer application remains below a certain threshold (a minimum required amount). In addition, substantial average yield improvements are observed under site-specific fertilizer application (8.4 tons/ha) in comparison to uniform application of fertilizers (2.0 tons/ha).

The study also demonstrates that homogeneous fertilizer application is less profitable than site-specific application, especially if the expected yield is about 2 tons/ha (DRC's national recommendation). We also found that the average profit margin is lower when spillovers are accounted for than when they are not included, but still higher with PA-guided application than under homogeneous application. Furthermore, excluding areas with lower expected yields than the national average results in a gross profit margin increase of 35.6 percent (under PA-guided application with spillovers) and 22.7 percent (under PA-guided application without spillovers).

Taking spatial spillovers into account does matter as farmers' profit margins fall when spillovers are not accounted for, even though they remain significantly higher under variable application compared to uniform application. Ignoring spillovers will therefore cause maize yields and farmers' profitability to become unpredictable, especially given the variability in soil and weather across different agro-ecological zones.

Compared to homogeneous fertilizer application, PA-guided fertilizer management has the potential to reduce total fertilizer costs, increase yields, and improve profitability. By providing insights into the effects of spatial spillovers in fertilizer application, our study contributes to a better understanding of the potential effects of field-specific fertilizer management on farmers' profitability and maize production.

Smallholder farmers in African countries could largely benefit from PA technologies and resulting site-specific input application. However, there are still obstacles that impede the possibility of wider PA adoption including limited farmer education and training programs as well as access to information and extension services.

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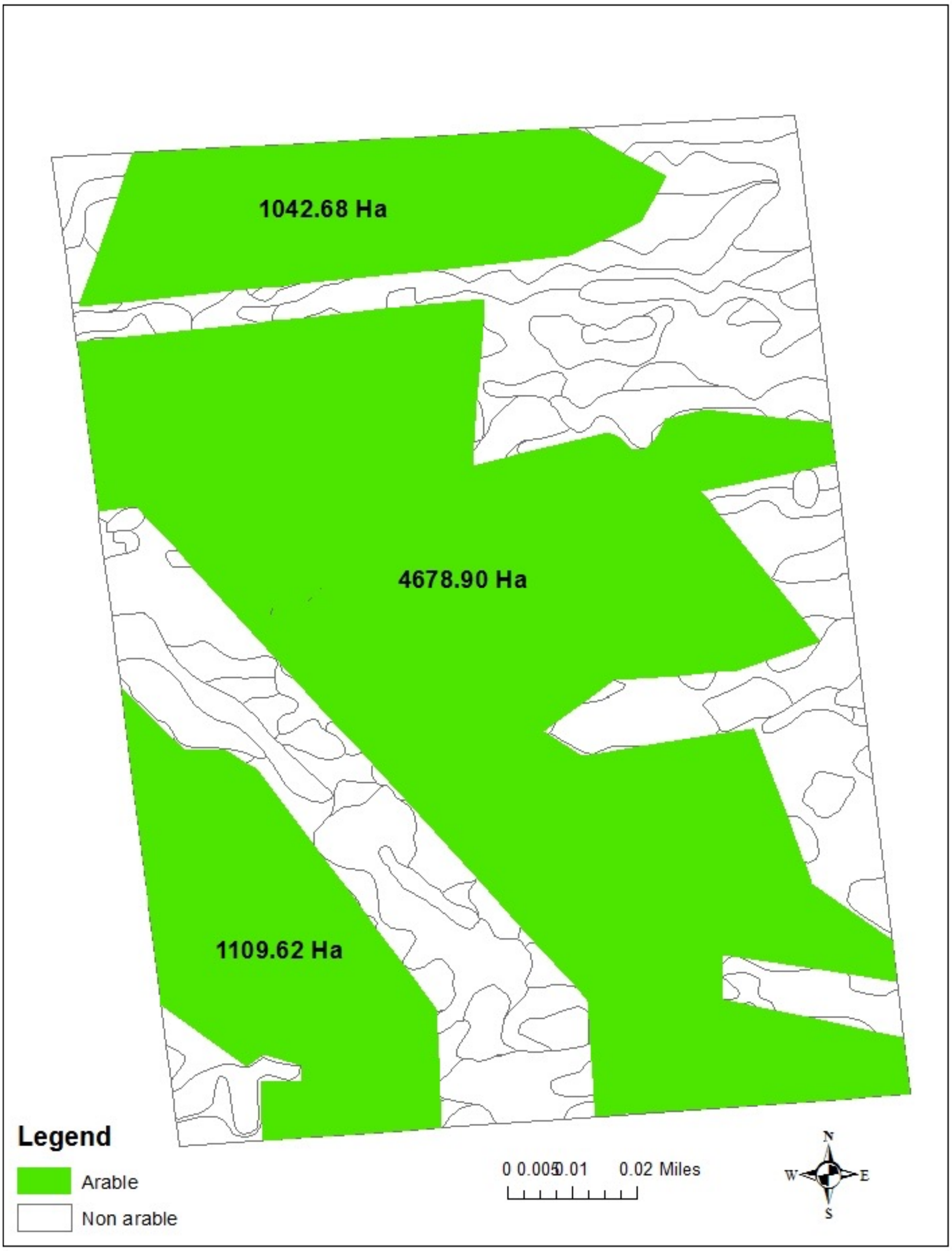
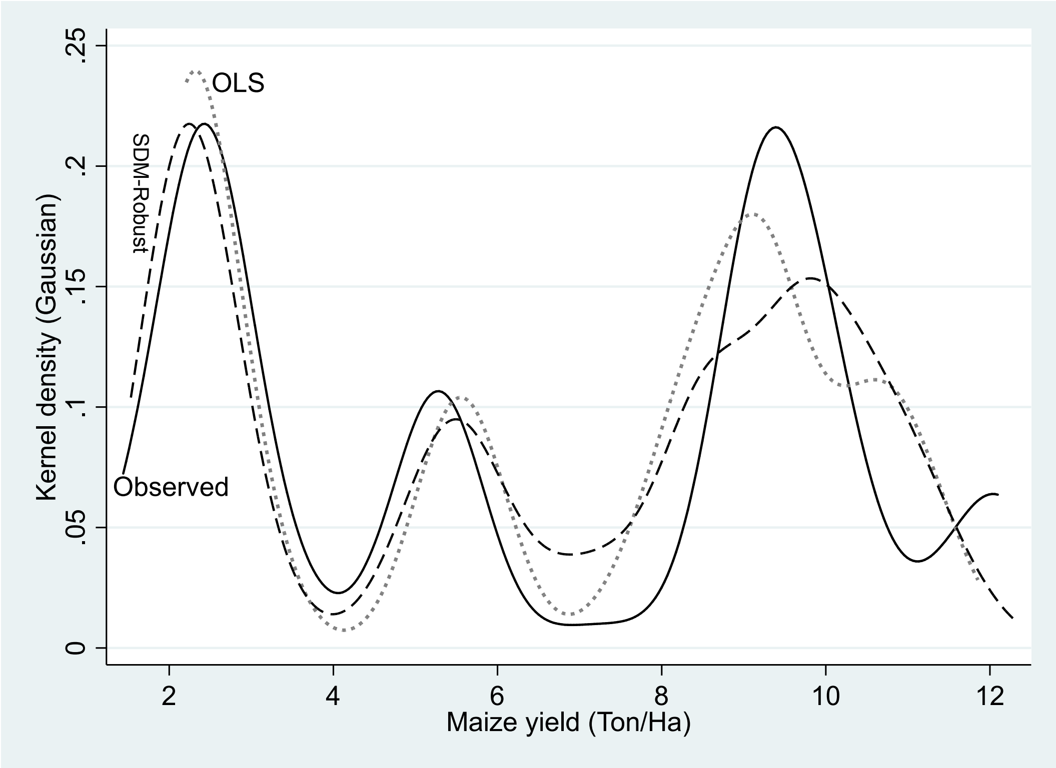
Annexes

Figure 1. *Arable Land with Expected Yield of at Least 2 tons/ha*



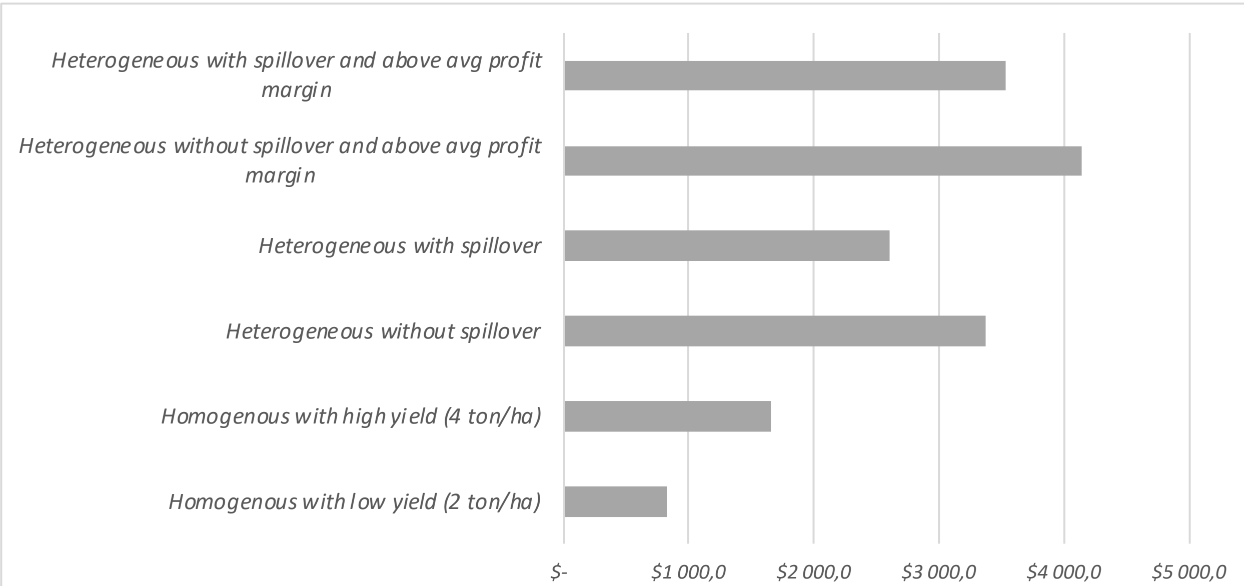
Source: AgriXcellence (2013)

Figure 2. Kernel Density of Maize Yield



Source: Estimated by the author.

Figure 3. Profit Margins Per Hectare – Homogeneous Fertilizer vs. Precision Farming Applications



Source: Calculated by the author.

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