Can Economic and Environmental Benefits Associated with Agricultural Intensification be Sustained at High Population Densities? A Farm Level Empirical Analysis

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Abstract

The Boserupian theory holds that population density growth can be accompanied by sustainable agricultural intensification (Boserup, 1965). However, it is not certain whether the positive link between population density and environmental/economic benefits associated with agricultural intensification are indefinite. The current study utilizes cross sectional data from a random sample of farm households drawn from two densely populated Counties in Kenya to assess whether Boserupian agricultural intensification is sustainable at high population densities. The study utilizes a robust approach that incorporates soil quality parameters into economic analysis to assess the effect of population density on soil quality and crop productivity. It employs non- parametric regression, OLS regression and asymmetric trans-log production function estimation methods. Results indicate that at low a population density, endogenous sustainable agricultural intensification occurs, which is associated with improvements in soil quality and crop yields. However, as population densities exceed 600 persons/Km^2, soil quality attributes such as soil texture, soil pH levels and fertility indicators such as soil organic matter (SOM) and electrical conductivity (EC) start to deteriorate. The end result of deteriorating soil quality is binding of critical nutrients and thus reduction in the crop yield response to fertilizer application. This reduces crop productivity and consequently returns to agriculture. These findings have imperative policy bearing on livelihoods and smallholder agriculture considering that a large proportion of sub-Saharan Africa's population is dependent on rain-fed agriculture and population densities continue grow.

Key words: *Population density; Intensification; soil quality; crop productivity*

1. Introduction

Population density growth is a critical agricultural development issue because of its impact on crop production through its effects on land availability and quality. There is a growing concern on the potential impacts of further population density growth especially in sub-Saharan Africa where a vast majority of households are largely dependent on rain-fed smallholder agriculture. Earlier studies argued that mounting population densities induces agricultural intensification. For example, the widely acclaimed "Machakos Miracle" as presented by Tiffen et al., (1994) portrayed a success story where growing population density was accompanied by Boserupian agricultural intensification. Agricultural intensification and productivity growth resulted from adoption of new technology, increased use of labor, fertilizer, and capital inputs per unit of cultivated land, and shorter fallow periods while at the same time reaping environmental and economic benefits through reversed land degradation and improved crop yields (Mortimore et al., 1991; Mortimore and Tiffen, 1994). Over 20 years have passed since the Machakos Miracle was documented. Machakos has undergone substantial transformations as population densities continues to rise, with some areas recording population densities of over 1000 persons/Km^2 (KNBS, 2010), and increased land scarcity (Willy et al., 2015). Farming systems have also changed with closing farm sizes accompanied by substantive land cover and land use changes. These changes are not unique to Machakos but are also characteristic of many parts of rural sub-Saharan Africa where agriculture remains a key livelihood strategy. Many parts of rural Kenya and indeed the East African region are experiencing population densities similar to or beyond those experienced in Machakos in 1990s. Consequently, an assessment of the endogenous evolution of farming systems in the county would be of major importance for anticipating the challenges that an increasingly densely populated East Africa region is likely to face. Unsustainable forms of intensification could lead to widespread deterioration of soil capital that could in return lead to *poverty traps* (Barrett, 2008). Given the important role of smallholder farming in the developing countries, the need for enhancing farmers' productivity through sustainable pathways is urgent.

The current study aims at assessing whether the agricultural intensification witnessed by Tiffen et al., (1994) in Machakos is sustainable at higher population densities and over a long period of time. Specifically, the study seeks to: (1) evaluate the trends in agricultural intensification in the context of growing population densities, (2) estimate the effect of population density, farmer practices, plot attributes and institutional factors on soil quality, and (3) estimate the maize yield response to growth and facilitating inputs while controlling for population density, plot level attributes, soil quality, soil conservation practices and fixed regional effects.

Population density and agricultural intensification

The debate on the link between population density and agricultural intensification is not a new one, and we note some issues that warrant methodological considerations. First, in evaluating the Machakos Miracle, critics have claimed that the effects observed by Tiffen et al., (1994) could have been confounded by the effect of proximity of Machakos to Nairobi, a major urban center. Zaal and Oostendorp, (2002) argue that the distance to urban centers was as important in explaining the driving force to investments on land conservation strategies as population density. Consequently, agricultural intensification is not merely a spontaneous endogenous process but could also be externally driven by policy and institutional factors. Proximity to urban centers for instance provides exit routes out of the farm to off farm employment and also provides a ready market for agricultural output. Access to urban markets not only offers opportunities for commercial farming but also facilitates further intensification since the surpluses generated from agricultural commercialization can also be used to finance further intensification. Therefore, it could be possible that the wide-spread intensification reported in Machakos was as a result of urban influence, institutional and policy factors and not necessarily driven by population density alone. Second, Murton, (1999, 1997) also questioned the use of highly aggregated data because of the possibility of masking effects. Third, despite the important effect of soil quality on crop productivity, we find a dearth of attempts in literature to incorporate soil quality parameters into economic analyses linking population density to agricultural productivity. Productivity gains associated with agricultural intensification may be short lived if such gains are not accompanied by long term improvements in soil quality.

The contribution of the current study to the population growth-agricultural intensification debate is three-fold. First, we test the 'more people less erosion' hypothesis using plot-level data to control for plot heterogeneity. Second, we assess the influence of agricultural intensification on the quality of soil and crop yields, while controlling for urban influence, institutional and policy factors. To control for urban influence, Kisii County, an area that is similar to Machakos in all other aspects except proximity to a major urban center is included in the study for comparison purposes. Third, as far as we know, there have been limited attempts in literature to combine socio-economic data and biophysical/chemical soil data in assessing the link between population density and agricultural sustainability. Our study therefore takes a rare approach that incorporates soil sample data into socioeconomic analysis to evaluate the sustainability of agricultural intensification in the face of growing population density. To do this, we revisit the areas where sustainable agricultural intensification was documented by Tiffen et al. over 20 years ago and assess how population density relates to soil quality and crop yields currently compared to then.

Conceptual Framework

The current study is concerned with the link between population density through direct influences and other intervening factors. Agricultural productivity can be influenced by multiple factors, which we can categorize into two main pathways. The first pathway of influence involves exogenous household and community socio-economic factors: household attributes, land tenure and population density. The second pathway is associated with factors that influence the growth of crops directly such as crop inputs and soil and water attributes. The conventional inputs (Seeds, Fertilizer, Labour, Land and Capital) have a direct influence on crop productivity and may change as population density grows, through the intensification process. Population induced agricultural intensification may not necessary follow a sustainable path. Recent studies (Muyanga and Jayne, 2014; Ricker-Gilbert et al., 2014) have identified population density thresholds beyond which the productivity gains associated with agricultural intensification start to vanish. Research has also revealed that although the green revolution had substantial success in saving forests, wetlands and improving peoples livelihoods, the productivity gains associated with it have since slowed (Pingali, 2012). This could be attributed to diminishing returns to labor and declining soil quality due to nutrient mining associated with shortened fallow periods. It is therefore critical to assess the trends in soil quality as population density increases. In the current study, soil quality is measured through Total Organic Carbon (TOC), Plant Available Phosphorus (PAP) and Electrical Conductivity (EC). TOC is critical to crop productivity given that plant nutrients are normally stored in the soil organic matter (SOM), which influences macro-nutrient (P and N) availability to plants through its influence on the mineralization process (Musinguzi et al., 2013; Bationo et al., 2007). When TOC levels are below the critical levels, the yield response to applied N is affected (Musinguzi et al., 2013). The levels of TOC are usually influenced by inherent soil properties such as soil texture, climatic conditions (precipitation and temperature) and management practices (use of crop residue, agroforestry, use of inorganic fertilizers and fallowing). Phosphorus (P) is a key macro-nutrient that is found in the soil either in organic or non-organic forms. Inorganic P may react readily with Aluminium (Al), Iron (Fe) and Calcium (Ca) ions to form insoluble compounds, meaning that only part of the P (referred to as the Plant Available P) is soluble and therefore can benefit plants. The soil electrical conductivity is important soil health indicators which measures the amount of salts in the soils and determines the soil water balance and micro-organism activity hence crop growth.

Description of the Study area

The current study was conducted in Machakos and Kisii Counties, Kenya (Figure1). Machakos County is located in Eastern Kenya at latitudes 0º 45′ South to 1º 31′ South and longitudes 36° 45′ east to 37° 45′ east, with an altitude range between 1000 and 1600 meters above sea level (m.a.s.l). The county covers approximately 6,208 Km^2 with an estimated population of 1,098,584 persons according to the 2009 Kenya population and housing census (KNBS, 2010). Kisii County is located south East of Lake Victoria in Western Kenya, on latitude: 0° 41' 0 S and longitude: 34° 46' 0 E. The county covers an estimated area of 1,317 Km^2, with a population of 1,152,282 persons and an average population density of 874 people per Km^2, according to the 2009 Kenya population and housing census (KNBS, 2010).

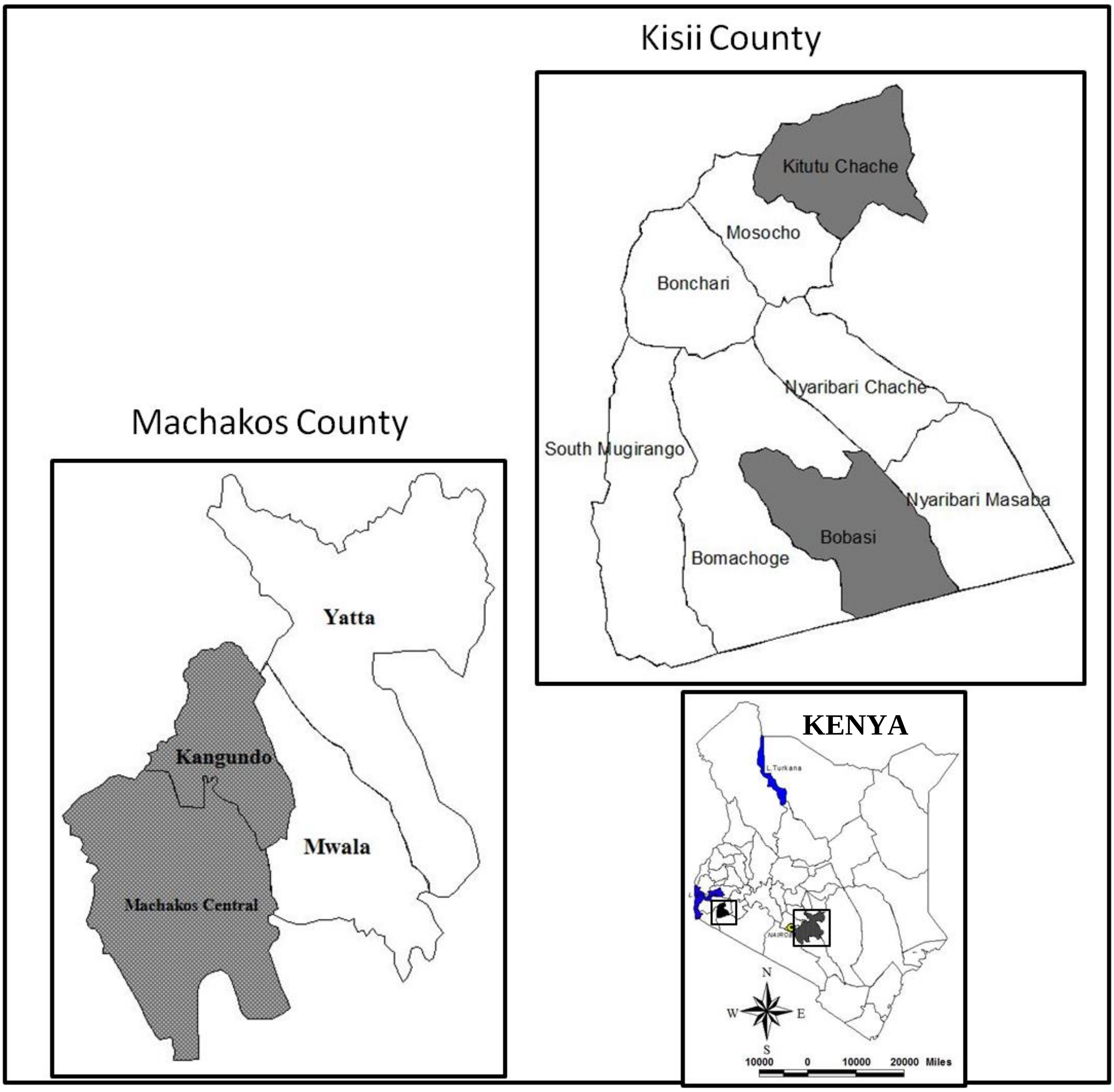

Figure 1: Maps of Kenya, Machakos and Kisii Counties showing location of study sites (shaded).

Data sources

The primary data used in this study were obtained through a cross-sectional survey among 290 randomly selected farm households located in densely populated regions of Machakos and Kisii counties, Kenya, between February and April 2014. Within each County, sub-counties were purposively selected based on population density estimates obtained from the Kenya National Bureau of Statistics (KNBS) population census data (Republic of Kenya, 2010). After the selection of the sub-counties, a multistage random sampling procedure was followed to select households. First, a random sample of Wards[1] was drawn, followed by a random sample of sub-locations and then villages. From each village, a sampling frame was developed with the help of village elders, from which a final random sample of farm households was drawn.

A pre-tested interview schedule was used to capture data on household socioeconomic and demographic aspects, crop and livestock production and marketing information, crop and livestock production inputs, historical land management practices, soil and water conservation practices and other relevant issues such as access to information, infrastructure, group membership and land markets. Population density data were obtained from the Kenya 2009 Census data base from the Kenya National Bureau of Statistics (KNBS, 2010). Further, soil samples were collected from the largest maize field in every sampled farm household, following a standardized soil sampling protocol. The analysis of soil samples was done using conventional procedures. Analysis of the available nutrients (P, N, K, Mg among others) followed the Mehlich Double Acid Method (Mehlich, 1953) while Total Organic Carbon (TOC) was estimated using the Walkey-Black method (Walkey, 1947). Detailed soil analysis procedures can be obtained from the authors upon request.

Analytical Framework

Three analytical methods were used in this study. *First*, bivariate non-parametric regression was used to ascertain whether the positive effects of population density on the environment (soil quality) and crop productivity (maize yields) can be sustained at high population densities. The *kennel density estimator* was used to assess the relationship between population density, soil quality parameters and crop productivity parameters.

Second, soil quality was modeled in the following generalized form:

$$SQ_i = f(m', \boldsymbol{\beta}, \boldsymbol{\varepsilon}) \quad \textbf{(1)}$$

[1] A Ward is fourth in the hierarchy of administrative units in Kenya.

where $SQ_i(i = 1,2,3)$ represents the soil quality parameters: CES, TOC and PAP. m' is a Kx1 vector of regressors, $\boldsymbol{\beta}$ is a Kx1 vector of coefficients to be estimated and ε is an error term. The regressors included in x are the factors that may influence soil quality directly such as the soil attributes, plot characteristics and management practices; and those that influence soil quality indirectly such as farmer attributes, regional factors and population density.

Third, to estimate the maize yield response to inputs while controlling for population density and other factors, we needed a modeling framework that can allow incorporation of factors that influence yields indirectly such as population density and household characteristics. In literature, we find widespread use of the translog and the cobb-Douglass production function in modelling yield response to inputs. However, these functional forms assume symmetry in the way inputs influence outputs and may not allow for accommodating of regressors that don't have a direct influence on output. To address this shortcoming, Guan et al., (2006) proposed a framework that accounts for the asymmetric influence of different types of inputs and other regressors on the output. This framework categorizes inputs into those that affect agronomic and growth aspects of crops directly such as fertilizers, land, seeds and water (growth inputs) and those that play a ''facilitative'' role such as labour, pesticides and capital (facilitative inputs). In the Guan et al., (2006) framework, the general crop production model may be specified as:

$$\boldsymbol{y} = \boldsymbol{H}(\boldsymbol{x}) \cdot \boldsymbol{F}(\boldsymbol{z}) \quad (2)$$

where y is the output, x represents growth inputs and z represents facilitating inputs. The $H(\cdot)$ component in (1) represents the attainable yields as determined by the conventional growth inputs: land, seeds and fertilizer. Soil quality variables may also be included among the growth inputs because soil attributes have direct effects on agronomic aspects of crop growth (Ekbom et al., 2013; Gray, 2011). Failure to include soil quality in the crop yield response function may bias the estimates in (2) (Ekbom et al., 2013). The scaling function $F(\cdot)$ represents factors have that have indirect effects on yields through their influence on the efficacy of the growth inputs. The facilitating inputs may go beyond the physical inputs such as labour, capital and pesticides to include community level factors such as population density and household socio-economic characteristics.

Empirical models

In this section, the relevant empirical models used in estimating (1) and (2) are specified. The influence of regressors on individual soil quality parameter was estimated through the following multiple regression model:

$$SQ = \alpha_0 + \sum_{k=1}^{3} \beta_k SC_{ki} + \sum_{j=1}^{9} \gamma_j MPRAC_{ji} + \sum_{h=1}^{5} \vartheta_h INST_{hi} + \sum_{m=1}^{7} \varphi_m SOCIOD_{mi} + \varepsilon_i \tag{3}$$

where SQ is the dependent variable capturing soil quality parameters (TOC, PAP and EC), α_0 is an intercept; SC is a vector of soil attribute regressors (N, P, pH), MPRAC are variables representing nine management practices (e.g. Terracing, use of crop residues, Use of hybrid varieties, Fallowing, Slash and burn, e.t.c). INST is a vector of regressors representing institutional and policy factors such as access to extension and markets, land tenure and agricultural wages, SOCIOD represents socio-demographic variables such as age and education level of household head, population density, household size and farm size. β_k, γ_j , ϑ_h and φ_m are coefficients to be estimated while ε is an error term that is assumed to be independent [$N(0,\ \sigma^2 I_N)$]. Equation (3) was estimated for each of the three soil quality parameters: TOC, EC and PAP. The regressors used in the model are presented in Table 1.

To estimate the yield response to growth and facilitating inputs, we specify the following asymmetric non-linear maize production function following the Guan et al., (2006) framework.

$$lnMZYIELD = \vartheta + \sum_{j=1}^{4} \alpha_j \cdot ln(x_{ji}) + \sum_{v=1}^{3} \emptyset_v \cdot ln(SQ_{vi}) + \left(\frac{1}{2}\right) \cdot \sum_{v=1}^{3} \sum_{j=1}^{4} \delta_{vj} \cdot ln(SQ_{vi}) \cdot ln(x_{ji}) + \left(\frac{1}{2}\right) \cdot \sum_{j=1}^{4} \sum_{k=1}^{4} \alpha_{jk} \cdot ln(x_{ji}) \cdot ln(x_{ki}) + \left(\frac{1}{2}\right) \cdot \sum_{v=1}^{3} \sum_{z=1}^{3} \omega_{vz} \cdot ln(SQ_{vi}) \cdot ln(SQ_{zi}) \cdot [\exp(-(\beta_0 + \left(\sum_{n=1}^{9} \beta_n z_{ni}\right))^2] + \varepsilon \tag{4}$$

where *lnMZYIELD* is the natural log of maize yields obtained in the sampled plot which was computed using the Liu and Myers (2009) approach which accounts for intercrops in the plots. SQ represents soil quality variables (TOC, PAP and EC); x represents growth inputs (quantity of Manure, quantity of N, Quantity of P and size of land); z represents the facilitating inputs (labour and Capital) and other relevant regional and farm specific attribute (population density, altitude, county dummy, soil conservation practices and input transport cost). ϑ, $\beta_0, \alpha_j, \emptyset_v, \delta_{vj}, \alpha_{jk}, \omega_{vz}$ and β_n are unknown parameters to be estimated. All the explanatory variables included in the model are described in Table 1.

While estimating equation (4), we note that soil quality is potentially endogenous because it depends on factors that cannot be accounted for directly in the model such as weather, geological conditions and farmer skills. The choice of the fertilizer input may also be endogenous given that farmers facing dry weather conditions may choose to apply low amounts of fertilizers making fertilizer quantities correlated with the error term. To deal with endogeneity problems, two remedies were used. First, we used the predicted values of soil quality parameters estimated from (1) to instrument for soil quality in the production function. Secondly, we controlled for fixed regional effects by including a county dummy and altitude among the facilitating variables in the production function. The county dummy also captures the effects of proximity to a major urban center. Equation (3) was estimated using OLS regression while equation (4) was estimated using the non-linear regression approach (nlsur) in STATA. The output elasticities, evaluated at the mean values were also estimated to identify the marginal productivity of inputs.

Results and Discussions

Descriptive Statistics on Household and Soil Quality attributes

This section presents descriptive statistics on all important variables used in this study as presented in Table 1. First the mean values are estimated for the entire sample and then at the population density quartiles.

Trends in the production variables reveal evidence of Boserupian type of intensification. While farm land is declining with the growth in population density, we observe that all the major inputs fertilizer, labor and capital were increasing with population density. Declining farm sizes are a clear indication of land scarcity driven by population density as people subdivide the scarce arable to cater for the increasing demand for crop land. In Machakos, available data indicates that farm sizes have fallen by over 50% between 1978 and 2015 (Murton, 1999). The decline in crop land has also been accompanied by a decline in the fallow land.

Agricultural intensification and the accompanying trends have implications on other farming practices. For instance, results indicate high levels of adoption of terracing practice, use of hybrid varieties and production of cash crops. All these are practices associated with agricultural intensification as farming systems undergo transitions in response to population density growth (Boserup, 1965). On the other hand, we see a decline in the use of crop residues, fallowing and agricultural mechanization as population density rises. Trends in these practices have far reaching implications on the sustainability of agriculture in the research areas.

Trends in soil quality parameters as can be used as indicators for sustainability in crop production. The quality of soils in the sampled plots was generally low given that level of Total organic carbon, Active carbon, Nitrogen, Cation Exchange Capacity (CEC) and Plant available Phosphorus were all below the critical levels. Poor soil quality can be attributed to poor management practices such as low use of organic manure and crop residues, continuous cultivation of the plots (on average 32 years) and reduced fallow periods. Inherent soil parameters such as pH and texture may also influence other soil parameters. For instance, at low pH levels, phosphate ions react with aluminum (Al) and iron (Fe) to form less soluble compounds (Truog, 1930) which are not available to plants. Soils in the study areas are generally acidic (average pH = 4.9) and sandy (55% on average) and this could explain why the soils are also low on PAP, CEC, TOC and AC.

Table 1: Description of Variables used in the Estimations

Variable	Description of the variables	Population Density Quartiles				
		1[Lowest]	2	3	4[Highest]	Overall
Maize Production variables						
MZYLD	Maize yield (Tons/ha)	1.2	1.1	0.9	1. 1	1.1
LAND	Amount of land owned (Ha)	0.6	0.9	0.6	0.4	0.6
MZLAND	Area under maize in hectares	0.4	0.3	0.3	0.3	0.3
FERT	Quantity of inorganic fertilizer (Kg/ha)	171.7	189.5	168.1	275.4	200.4
N	Quantity of Nitrogen applied (Kg/ha)	53.2	72.9	45.7	58.7	57.4
P	Quantity of Phosphorus applied (Kg/ha)	34.7	51.0	26.7	33.0	36.2
CAPITAL	Capital Input ('000 Ksh/ha)	17.0	13.0	16.0	21.0	17.0
MAN	Quantity of manure applied (Tons/ha)	3.3	1.9	2.1	1.8	2.2
TOTLAB	Labour input per (Mandays/Ha)	139.3	122.9	140.9	153.5	139.3
HIRELAB	Hired labour input (Mandays/Ha)	108.2	96.5	77.7	74.2	89.3
FAMLAB	Family labour (Mandays/Ha)	102.4	71.6	77.4	89.3	85.1
Management Practices						
TERR	Terracing implemented (Yes=1)	0.9	0.7	0.6	0.5	0.7
RESID	Incorporation of crop residues(Yes=1)	0.5	0.4	0.5	0.5	0.5
CASHCROP	Farmer growing cash crops (Yes=1)	0.8	0.7	0.5	0.7	0.7
HYBRID	Farmer planted hybrid variety (Yes=1)	0.9	0.8	0.8	0.8	0.8
MECH	Mechanized land preparation (Yes=1)	0.04	0.07	0.01	0	0.03
SBURN	Slush and burn practice (Yes=1)	0.1	0.1	0.1	0.21	0.13
FALLOW	Fallow Land in the last 5 years (%)	0.2	0.7	2.0	0.6	0.9
DUR	Duration of plot use (years)	40.1	33.1	32.0	26.2	32.9
Soil Quality attributes[2]						
TOC	Total organic Carbon (% value)	1.7	1.5	2.0	2.11	1.8
PAP	Plant available Phosphorus (ppm)	12.1	17.4	21.1	13.0	15.9
EC	Electrical Conductivity (ms/Cm)	0.07	0.06	0.08	0.09	0.07
SAND	Sand content in soil (%)	55.6	62.0	59.9	51.0	57.2
pH	Soil pH-H_20-1:2.5	5.8	5.9	5.8	5.5	5.7
PLOTDIST	Walking time to the plot (Minutes)	5.3	3.9	6.5	4.0	4.9
Demographic attributes						
AGE	Age of household head (Years)	61.2	55.9	53.7	51.2	55.6
HHSIZE	Household size (Adult Equivalents)	2.8	2.9	3.5	2.8	3.0
EDUC	Household head education level (Yrs)	7.9	7.8	8.8	8.4	8.2
Community level factors						
POPDENS	Population density (Persons/Km^2)	507	543	654	843	635
MZTRANS	Cost of transporting maize (Ksh/Km)	53.4	89.1	72.5	38.3	63.5
EXTDIST	Distance to extension service (Km)	5.4	5.1	6.3	5.9	5.7
NCPB	Distance to the nearest NCPB depot (Km)	10.4	9.8	16.8	20.2	14.3
WAGE	Wage rate at village averages (Ksh/Md)	194.5	186.0	148.9	117.6	162.1
DAPRICE	Price of DAP fertilizer (Ksh/Kg)	77.0	79.6	77.9	76.3	77.5
DISTOWN	Distance to the nearest town (Kms)	4.6	4.3	2.9	4.6	4.2
ALT	Altitude (meters above sea level)	1,718	1740	1846	1767	1767
TENURE	Land tenure (Secure=1)	0.4	0.3	0.2	0.2	0.3

Source: GISAIA Survey data, 2014

Community and regional level factors are also critical in explaining trends in crop productivity. The average population density in the study areas is 635 which is way above the average when the More people less erosion study was conducted. The wage rate is seen to be

[2] These values can be compared with the critical values (Aune and Lal, 1997 ; Weeda, 1987): TOC-2%; N-0.2% PAP-20ppm

declining with the growth in population density implying surplus in the labour market that is characteristic of densely populated areas. There is generally improved access to markets and extension services as well as decline in the transaction costs. These trends indicate improvement in infrastructure and government support as population density grows.

Non-Parametric Regression Results

In this section we present results generated through non-parametric regressions between population density and soil quality & crop productivity parameters. As shown in Figures 2, 3 and 4, all the three soil quality parameters (TOC, CEC and PAP) first increased with population density growth, reaching a saddle point at approximately 600 persons/Km2 and then start to decline. EC on the other hand increases with population density growth. At lower population densities, soil quality seems to be improving, consistent with the findings of Tiffen et al., (1994). However, beyond the 600 persons per Km^2 population density threshold, the gains associated with agricultural intensification start to decline. The findings in this study concur with recent findings from studies in some African Countries assessing the impact of population densities to changes in farm structures (see Josephson et al., (2014); Muyanga and Jayne, (2014); Ricker-Gilbert et al., (2014)).

Figure 5 shows a nonlinear relationship between cropping income (Ksh/Ha) and population density with a saddle point at 600 persons/Km^2. This coincides with the point when soil quality also starts to decline. Returns to investment in agriculture, as measured by the maize yield per capital input, was also found to be declining at high population densities. Low returns to agriculture can be a disincentive towards further investment in agriculture and therefore may lead to exits from farming provided alternatives exist. The decline may be attributable to the decline in agricultural wages and returns to labour as population grows. As Binswanger and Pingali, (1998) argue, in the process of agricultural intensification, there is some degree of substitutability of capital and labour for land to the extent that the returns to labour decline with growth in population densities.

The results in Figure 7 indicate that the maize yield per Kg of inorganic fertilizer applied starts to decline after the 50^{th} percentile or at approximately 600 persons per Km^2. Further, there is an improvement in NUE at lower population densities which starts to decline at population densities exceeding 650 persons/Km^2. Nitrogen use efficiency relates to the ability of crops to absorb N and utilize it to generate yields and is measured by the quantity of Maize output (Kg) per Kg of Nitrogen applied. NUE is highly influenced by soil parameters such as texture and the level of plant available Phosphorus.

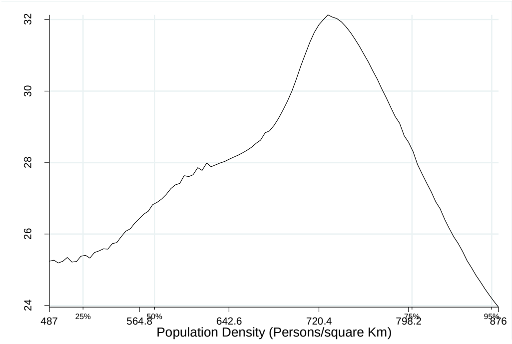

Figure 2: Population density vs CEC

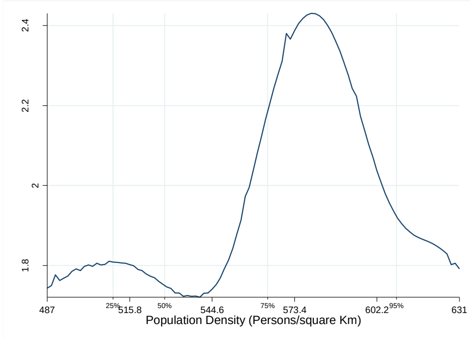

Figure 3: Population density vs TOC

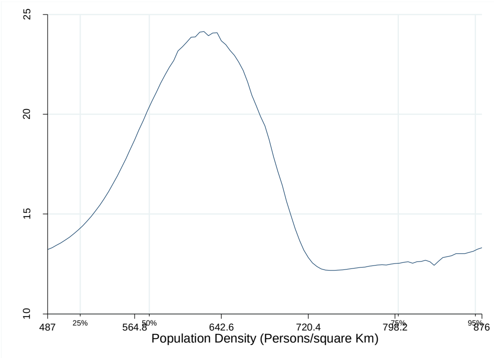

Figure 4:Population density vs PAP

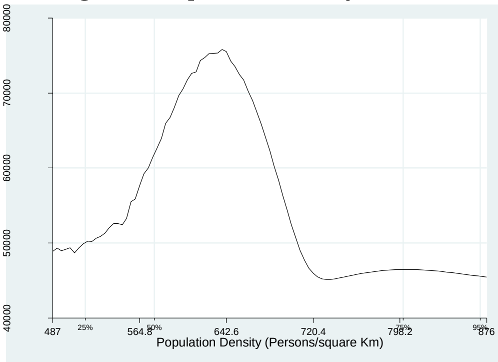

Figure 5: Net crop Income (Ksh/Ha):

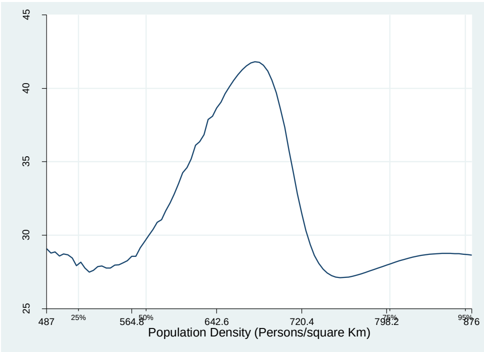

Figure 6: Nitrogen Use efficiency (KgMaize/KgN)

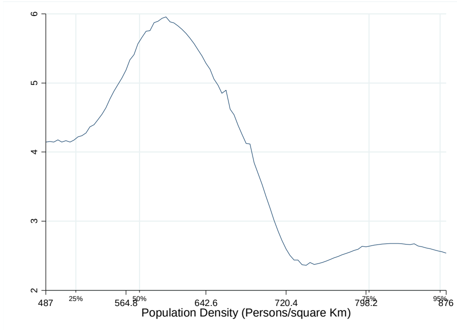

Figure 7:Population density Vs Maize yield/Kg Fertilizer

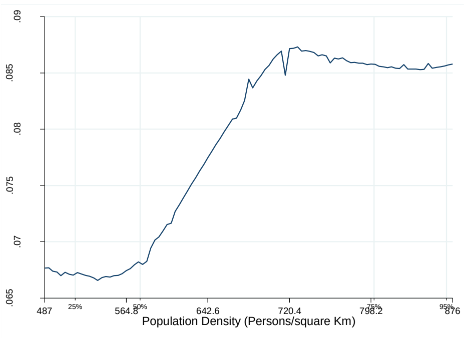

Figure 8: Electrical Conductivity (mS/cm)

Regression Analysis Results

Although the non-parametric regression results provide clear trends on the relationship between population density and soil quality, one weakness of this method is that is does not allow for controlling of other important factors that could influence soil quality and crop productivity. To achieve this objective, we followed up with multiple OLS regression models. To assess the effect of population density on soil quality, we estimated six models (Table 2), two for each dependent variable. In each case, the first model was estimated using plot level explanatory variables while the second model, we added household, community and regional level explanatory variables.

Across the three models, we observed a substantial change in coefficient estimates and the coefficient of determination (R^2) once we control for fixed regional and village fixed effects. This implies that soil quality cannot just be explained by plot variables alone but village and regional heterogeneity contributes substantially to soil quality.

Table 2: OLS Regression results: Determinants of quality of Soil

	PAP		TOC		EC	
	MODELI	**MODELII**	**MODELI**	**MODELII**	**MODELI**	**MODELII**
LAND	1.49* (0.83)	0.62 (0.75)	0.03 (0.04)	0.02 (0.03)	-0.00138 (0.00203)	-0.001 (0.002)
DURUSE	-0.01 (0.04)	0.00 (0.04)	0.00 (0.00)	0.00 (0.00)	0.00005 (0.00010)	0.000 (0.003)
FALL	-0.63 (0.71)	-0.56 (0.63)	0.06* (0.03)	0.07** (0.03)	0.00212 (0.00174)	0.002 (0.001)
TERR	2.52 (1.99)	3.03* (1.75)	0.03 (0.09)	-0.01 (0.08)	0.00353 (0.00488)	0.003 (0.002)
HYBDIR	-3.41 (2.29)	1.06 (2.05)	-0.03 (0.10)	-0.05 (0.09)	0.00953* (0.00561)	0.009 (0.01)
MECHANIZ	2.60 (5.46)	0.98 (4.83)	-0.84*** (0.24)	-0.55*** (0.21)	-0.00575 (0.01338)	0.002 (0.01)
RESID	1.16 (1.65)	0.75 (1.49)	0.06 (0.07)	0.04 (0.06)	-0.00254 (0.00405)	-0.005 (0.00)
SBURN	0.17 (2.53)	0.58 (2.22)	0.02 (0.11)	-0.03 (0.10)	0.00094 (0.00621)	-0.003 (0.01)
MANURE	0.69** (0.28)	0.55** (0.25)	0.01 (0.01)	0.001 (0.01)	-0.00010 (0.00068)	0.000 (0.00)
N	0.04** (0.02)	0.03* (0.02)	0.00** (0.00)	0.001 (0.00)	-0.00010** (0.00005)	0.000 (0.00)
P	-0.04 (0.03)	-0.03 (0.03)	0.00* (0.00)	0.001 (0.00)	0.00021** (0.00008)	0.003** (0.00)
SAND	0.13* (0.07)	-0.14** (0.07)	-0.01*** (0.00)	-0.01*** (0.00)	-0.00087*** (0.00017)	-0.001*** (0.00)
pH	8.06*** (1.37)	7.51*** (1.32)	-0.05 (0.06)	0.00 (0.06)	0.02025*** (0.00337)	0.025*** (0.00)
CASHCROP	-1.85 (1.83)	1.45 (1.84)	-0.19** (0.08)	0.04 (0.08)	0.00191 (0.00448)	0.003 (0.01)
COUNTY		7.63 (5.15)		0.36 (0.22)		-0.027** (0.01)
PDENSITY		1.04***(0.13)		0.001 (0.01)		-1.7e-04 (3.6e-04)
PDENSITY2		-0.001 (0.00)		-0.001 (0.00)		1.0e-07 (2.3e-07)
NCPB		-0.08 (0.12)		0.01* (0.01)		-1.9e-04 (3.2e-04)
TCOST		0.001 (0.00)		0.00 (0.00)		-1.0e-06 (1.3e-04)
WAGE		0.24***(0.06)		0.00 (0.00)		-2.3e-04 (1.5e-04)
EXTACCE		-0.03 (0.18)		-0.01 (0.01)		9.5 e-04 (5.0e-04)
DAPPRICE		-0.17**(0.09)		0.02*** (0.01)		3.9e-04 (2.4e-04)
TENURE		-0.92 (1.75)		0.05 (0.08)		3.4e-03 (4.8e-03)
HHSIZE		-0.74 (0.57)		0.02 (0.02)		-4.3e-05 (1.6e-04)
EDUC		0.22** (0.10)		0.00 (0.00)		1.4e-04 (2.8e-04)
AGE		0.06 (0.05)		0.00 (0.00)		-1.1e-04 (1.5e-04)
DTOWN		0.08 (0.16)		-0.02** (0.01)		-9.9e-04 (4.4e-04)
ALT		-0.02 (0.01)		0.002*** (0.00)		7.2e-06 (2.2e-06)
INTERCEPT	-4.07 (8.63)	-3.91 (4.51)	2. 92(0.38)	-3.38* (1.97)	0.001*** (0.02)	0.012 (0.12)
R^2	0.22	0.45	0.16	0.42	o.20	0.30

Figures in parentheses are robust standard errors; In each case, MODELI analyzes the effect of plot level variables while MODEL II modifies model I by adding regional and community variables.

Results presented in Table 3 indicate that fallowing influences TOC positively. Fallowing allows the build-up of soil organic matter as opposed to year-long cultivation cycles. Mechanized land preparation had a negative influence on TOC because mechanized land preparation highly disturbs the soil structure hence accelerating the breakdown of organic carbon. The sand content of the soil had a negative effect on TOC. Soils with higher percentages of sand are poor preservatives of soil organic carbon while those rich in clay normally slow down the decomposition of soil organic matter and therefore preserve it. As indicated in **Error! Reference source not found.**, soils in the research area are mainly Sandy and therefore this could partly explain this result. Farms where cash crops (tea and coffee) were grown also had lower TOC. This could be linked to the high levels of intensification in such farms which could work against SOM build-up. The important community level factors were DAP price, the distance to the NCPB and altitude. Higher DAP prices are likely to discourage the use of inorganic fertilizers and encourage the use of manure, hence the positive effect. Farms located in high altitude areas are likely to receive higher precipitation which is linked to higher production of plant biomass and therefore higher organic carbon. Institutional support seems to work against soil organic matter build-up, possibly as a result access to subsidized inorganic fertilizers that are supplied through the NCPB.

Plant available phosphorus (PAP) was positively influenced by the amount of manure applied. Manure is rich in phosphorus and unlike inorganic fertilizer, manure does not lower soil pH and most of the P in manure is available to plants. As expected, soil pH had a strong positive effect on PAP. At lower pH levels, phosphorus is normally bound through the formation of insoluble compounds (Truog, 1930). Soil conservation through terracing had a positive effect on PAP. Soil conservation preserves the top soil and therefore helps in the buildup of soil nutrients and improvement in crop yields (Ekbom et al., 2013; Willy et al., 2014).

The coefficient of the amount of Nitrogen in the electrical conductivity model was negative. This relationship could be linked to the fact that high levels of EC lead to loss of nitrogen which will in return impact on crop growth negatively. Soil pH was also found to influence EC positively. Soils from Machakos were found to have higher EC implying that they were more saline. The lower EC levels in Machakos could be attributed to soil types in Machakos and intensive land management practices.

Finally, population density had a nonlinear relationship with all the soil fertility parameters as indicated by the coefficient of population density and its squared terms in all the models, a result that is consistent with the descriptive analysis results presented earlier.

The cost of transporting maize to the market, an indicator of market access (which could also imply transaction costs) had a positive relationship with all soil fertility indicators. Farmers facing high transaction costs related to infrastructural challenges are also likely to face high fertilizer prices and scarcity. As a result, they are more likely to implement non-market based measures of soil fertility management strategies such as manure application and labour intensive soil conservation practices.

Production function estimation results

The yield response estimates from the production function are presented in Table 4 while the output elasticity of selected variables is presented in Figure 9.

Population density had a negative effect on maize yields, confirming the hypothesis that crop yields will tend to decline with population density growth, *ceteris peribus*. As Muyanga and Jayne, (2014) point out, the effect of population density on crop output is normally indirect through the effect of population density growth on prices and land holding. In addition, we find that this influence could be through changes in soil quality associated with population density growth. The other regional factors that had a significant effect on crop yields included county dummy and altitude. Maize yields were higher in Kisii County owing to favorable weather conditions and better soil quality. Farms located in higher altitude areas also had better yields because of the strong correlation between altitude and weather parameters such as rainfall and temperature.

The output elasticity of land was -2.2% indicating an inverse land size-yield relationship a finding that concurs with those of Ünal, (2008) and Pieralli, (2014). Some of the popular arguments to explain the inverse land size-yield relationship found in literature include crop diversity (Griffin et al., 2002); land and labour market imperfections (Ali and Deininger, 2014; Holden and Fisher, 2013) and high labour input (Ünal, 2008). Better soil quality may make the inverse land yield effect even more prominent as seen in the highly statistically significant coefficients of the interaction terms between land size and all the soil quality parameters.

The elasticity of the nutrients, N and P was 2.4% and 1.8% respectively, while that of manure was 5%. The higher output elasticity of manure indicates that the use of organic fertilizers has a more potential for increasing output possibly because of the ability to improve soil organic matter. The effect of these macro-nutrients on crop output was found to be boosted by soil quality. The interaction term between N and TOC was positive and significant with an elasticity of 0.9% while the interaction term between P and TOC had an elasticity of 0.6%.

Table 4: Estimation results of Asymmetric production function

Variable	Estimate	Std. Err.	P>z
Land	-37.8***	0.058	0.000
N	22.7***	0.033	0.000
P	0.26	0.000	0.202
Manure	1.2	0.020	0.563
PAP	39.0***	0.048	0.000
TOC	159.6***	0.180	0.000
EC	-447.4***	0.070	0.000
$Land^2$	-0.56	0.008	0.455
N^2	1.4**	0.006	0.025
$Phos^2$	1.4**	0.004	0.010
$Manure^2$	0.12**	0.001	0.034
PAP^2	0.73**	0.004	0.048
TOC^2	6.5	0.041	0.111
EC^2	-62.2***	0.020	0.000
LANDXN	1.04	0.008	0.196
LANDXP	-0.54	0.009	0.580
LANDXMANURE	0.44***	0.001	0.010
LANDXPAP	1.52**	0.007	0.026
LANDXTOC	8.23***	0.019	0.000
LANDXEC	-9.23***	0.016	0.000
NXP	-3.5***	0.009	0.001
NXManure	0.16	0.002	0.563
NXPAP	-0.62	0.006	0.336
NXTOC	0.53	.0227	0.814
NXEC	8.63***	0.014	0.000
PXMAN	-0.23	0.002	0.246
PXPAP	0..32	0.007	0.644
PXTOC	0.71	0.012	0.555
PXEC	-2.1*	0.011	0.065
MANXPAP	-0.2	0.002	0.194
MANXTOC	-1.0*	0.006	0.094
MANXEC	0.1	0.006	0.866
PAPXEC	11.5***	0.014	0.000
TOCXEC	51.6***	0.062	0.000
Intercept	-2.5	0.621	0.967
CONT	-0.83***	0.002	0.000
TERRACE	0.026	0.001	0.625
CRESIDUE	-0.015**	0.000	0.038
POPDENSITY	-29.3	0.189	0.121
TCOST	0.035	0.000	0.175
CASHCROP	-0.077	0.001	0.161
ALT	.0146***	.0056	0.010
LNLABOUR	0.014	0.000	0.291
LNCAPITAL	0.005	0.000	0.557

*,**,*** parameters are significant at the 0.1, 0.05 and 0.01 levels respectively.

Soil quality was found to be a critical boost on maize output. Among the soil quality parameters, total organic carbon had the highest elasticity (2.4%) followed by PAP (1.7%). Soil quality improves the yields by enhancing the ability of the crops to absorb nutrients more efficiently hence boosting the crop yield response to fertilizers (Ekbom et al., 2013; Marenya and Barrett, 2009; Xu et al., 2009).The elasticity of EC on the other hand was significant and negative as expected, implying a negative effect of salinity on crop yields. Although this negative effect is likely to be reduced at higher levels of plant available phosphorus adding more nitrogen will make the effect even worse.

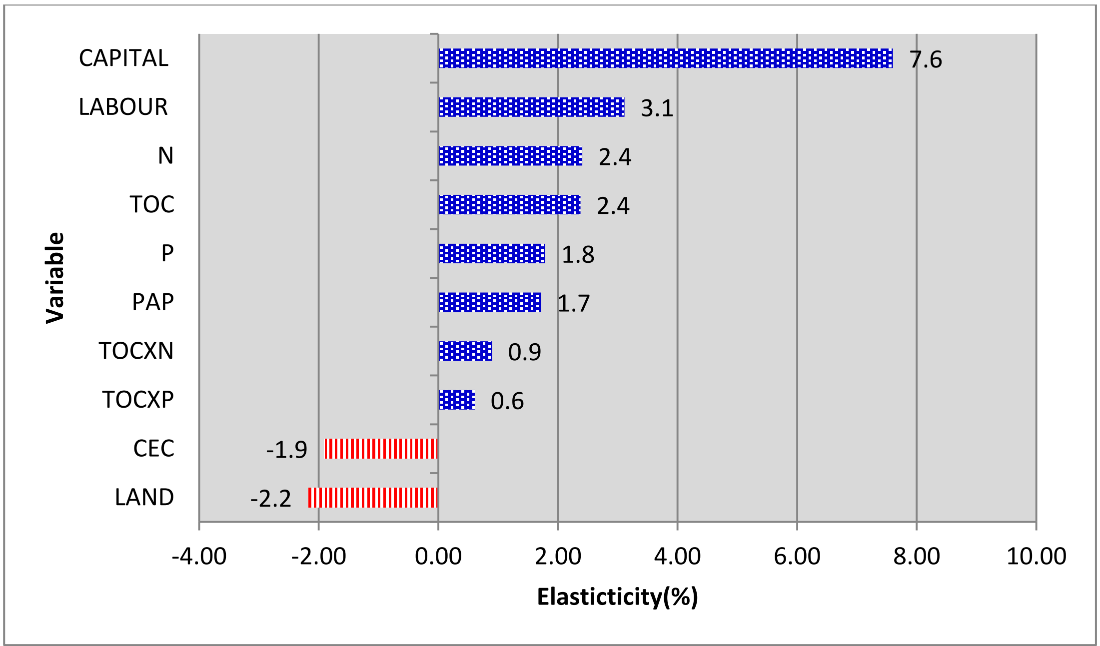

Figure 9: Output elasticities of selected explanatory variables

Finally, the output elasticity of Labour and Capital were 3.1% and 7.6% respectively. The lower labour productivity relative to capital implies labour abundance that is characteristic of densely populated areas. As population density increases, labour productivity decline as a result of substitutability between labour and capital (Binswanger and Pingali, 1998).

Conclusions and Policy Implications

The current study finds that although sustainable agricultural intensification can be possible at relatively low population densities, the gains associated with the Boserupian kind of intensification start to diminish as population densities go beyond the 600 persons/Km^2 threshold. After this population density threshold is reached, sustainable agricultural intensification declines with consequences on agricultural productivity. Endogenous technological change seems sufficient to drive agricultural growth at low population density as also observed by (Binswanger and Pingali, 1998) but may be limited at higher densities.

Our results reveal that at population densities beyond 600 persons/Km^2, farmers engage in excessive agricultural intensification where fallows almost disappear and there is continuous use of the same inorganic fertilizers without substantial efforts to replenish soil organic matter. As a result, the soil quality substantially declines as indicated by high levels of soil acidity, deterioration of soil texture (soils become sandier), and decline in inherent soil fertility as measured by Total organic Carbon and plant available Phosphorus. The decline in soil quality can affect crop yields through a chain of processes. Soil acidity causes critical nutrients to be bound in the soil in forms that are not accessible to the plants as manifested in the low levels of plant available phosphorus. High levels of acidity may also facilitate the increase in the level of toxic elements such as aluminium and manganese. A combination of soil acidity, poor texture and low plant available phosphorus causes a reduction in the Nitrogen use efficiency therefore leading to low yield responses to fertilizer use. The low yield response to fertilizer affects crop yields and eventually causes returns to investment in agriculture to decline. Low crop yields in small holder agriculture in Africa are counterproductive particularly to food self-sufficiency goals. Low returns to agricultural land and labour would also discourage investment in agriculture, encouraging exits from farming. In the densely populated areas of Kenya, exiting from Agriculture would rather not be a viable option because there are limited opportunities in the non-farm sector which does not grow at a reasonable rate to absorb substantial numbers of new and existing labourers to provide an alternative to the farming sector. This challenge is likely to persist especially because the population in SSA is projected to reach 2.4 billion by 2050 (Haub and Kaneda, 2013) by 2050, with a projected 330 million young Africans joining the job market in the next two decades (Jayne and Traub, 2016).

Agricultural policies in the future must therefore deal with the issue of unsustainable intensification in densely populated areas for as long as masses in these areas are still trapped in agriculture. There is need for a more focused and careful approach to soil quality management while enhancing strategic institutional support. Acidity was found to be a major problem among the soils in the densely populated areas, a problem that needs to be addressed. One of the major causes of soil acidity was identified as the over use of acidic fertilizers such as DAP. On farm soil testing and advisory services on appropriate fertilizer types are encouraged. Measures to enhance access to low cost soil testing services such as subsidized and decentralized soil testing facilities can help to solve the challenge. Although the private sector plays a critical role in providing advisory services, concentrating advisory information mostly on private input dealers may bias such information towards promotion of certain fertilizer types without necessarily considering specific field conditions. Technical advice on appropriate fertilizer combinations that are able to achieve nutrient replenishment without further deteriorating the soil quality are needed. Awareness on the importance of soil testing and improved access to soil testing facilities by resource poor farmers is also encouraged. Incentives to encourage liming of soils in the study areas such as improved access to subsidized agricultural lime can be a critical step. The challenge of organic matter decay can be addressed through encouraging practices that build organic matter such as incorporation of crop residues, avoiding slash and burn practices and also encourage incorporation of organic manure on the soils.

It is clear that most small-holder farmers in Sub-Saharan Africa are likely to face further declines in productivity, with serious consequences on food security goals. Towards a more firm policy advice, we recommend the quantification of the rate of soil quality deterioration at different population density levels and management practices.

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