Population Pressure and Soil Quality in Sub-Saharan Africa: Panel Evidence from Kenya

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Abstract

Population pressure on farmlands can have two opposing effects on soil quality. It can negatively affect soil quality due to more frequent and intensive use of farmlands, but also can induce transition of farming methods towards more intensive farming in which more fertilizer and improved seeds are used in order to make smaller farmlands more productive. In Sub-Saharan Africa, the net effect is likely to be negative given the region's low fertilizer use. Recent studies, however, show evidence of agricultural intensification in regions with high population pressure. It is important to analyze the extent and speed of soil degradation and its relationship with population pressure. Nonetheless, empirical studies on this topic are almost non-existent, partly because soil quality is shaped over a long time horizon, and quality panel data on this issue are rare. We use unique panel data for rural households containing soil quality information from Kenya to elucidate the effect of population pressure on soil quality. We find that population pressure reduces soil quality and also induces agricultural intensification. This suggests that although farmers are trying to mitigate the negative effect of population pressure on soil quality, the rate of soil degradation is outpacing that of intensification.

Keywords: population pressure; soil quality; soil degradation; agricultural intensification.

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1 Introduction

The livelihoods of many rural households in Sub-Saharan African (SSA) largely depend on agricultural activities. Estimates suggest that about two-thirds of the 974 million people in SSA live in rural areas and heavily rely on agriculture (World Bank, 2016).[1] This overreliance on agriculture suggests that land is one of the most important natural resources for the livelihoods of rural households in the region. Even though SSA is endowed with abundant land compared to other regions such as East Asia, available arable land per person has decreased and continues to decline (Jayne and Muyanga, 2012; Otsuka and Place, 2015). For example, between 1961 and 2011 arable land per person declined from 0.65 ha to 0.4 ha (Otsuka and Place, 2015).

Moreover, although agricultural sector remains to be one of the most important sectors in SSA; its performance has not been encouraging and it is considered as one of the worst in the world (Sanchez, 2002; Otsuka and Larson, 2016). The sector's poor performance is revealed in many areas including decline in food production. Since 1970 food production per capita in SSA has declined by 17% (Ehui and Pender, 2005). This trend not only makes SSA one of the regions threatened by food insecurity (Ricker-Gilbert et al., 2014; FAO, 2015a), but also it has implications on widespread rural poverty found in the region. Due to the sector's poor performance, it is not surprising that majority of SSA countries have remained net food importers.

[1]https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS

The decline in agricultural productivity in SSA can be attributed to many factors, one of them being declining soil fertility (Sanchez, 2002). The contributing factors to land deterioration widely cited in the literature include poor farming practices, inadequate land management, deforestation, and use of marginal lands (Morris et al., 2007). One of the major underlying causes is population pressure (Mortimore, 1993). At the same time, evidences indicate that the region's fertilizer use intensity is very low. For example, available data indicate that fertilizer use intensity in SSA is 14.9 kg/ha, a figure which is very low compared to the world average of 124 kg/ha, and that of East Asia and the Pacific which is 322 kg/ha (FAO, 2015b).

Whilst SSA has the lowest fertilizer use intensity, the rate at which soil fertility depletion is taking place in the region is quite high (Smaling et al., 1997; Henao and Baanante, 2006). For example, from 2002 to 2004 SSA lost Nitrogen, Phosphorous and Potassium (NPK) soil nutrients at a rate of more than 30 kg/ha per year in 85% of the African farmland (Henao and Baanante, 2006). Similarly, Sommer et al., (2013) note that the average combined depletion rate of NPK for all SSA in the past decades is 54kg/ha per year, and as of 2010 no any SSA country used 50 kg/ha per year.[2] This trend suggests that without thorough measures to address the problem, soil degradation is likely to affect rural farmers in many ways including food shortage and income poverty.

Surprisingly, although it appears that soil fertility decline is one of the critical problems impeding agricultural development in the region, there is a paucity of empirical studies that have

[2]A target that was set during Abuja Declaration on Fertilizer for the African Green Revolution in 2006. It required all SSA countries to use an average of 50/kg/ha per year by 2015 (IFDC, 2006).

examined the issue. By using Kenya as a case study, this study aims at filling this literature gap by examining how population pressure affect soil fertility. Kenya is an interesting case study. First, out of her total land mass of about 587,000 square km only 16% is arable land. Moreover, it is one of the countries in SSA which are experiencing shrinkage in arable land resulting from high population growth (Jayne et al., 2003; Otsuka and Place, 2015). In addition, like other East African countries; historically, Kenya's soils were very fertile especially on high-altitude areas. The country, however, has not been free from soil degradation (Drechsel et al., 2001; Henao and Baanante, 2006). Nevertheless, compared to other SSA countries, Kenya's fertilizer use intensity of 36.5 kg/ha is relatively better (FAO, 2015b). Soil quality[3] exhaustion amidst shrinkage of arable land is likely to affect this country whose 70% of its population is employed in the agricultural sector, and about 27% of its GDP comes from the sector (Kenya National Bureau of Statistics, 2015).

This paper examines the drivers of soil quality with a particular focus on rural population pressure on farmlands. First, we explore the effect of population pressure on soil quality. Subsequently, we examine the impact of population pressure on agricultural intensification[4]. We use geo-referenced panel data from Research on Poverty, Environment and Agricultural Technology (RePEAT). We supplement this data with population density data sourced from Kenya National Bureau of Statistics (KNBS), and agroclimatology data from National

[3]We use soil quality index constructed by using a number of soil macronutrients and chemical properties to define soil quality. The details on how the index is constructed are provided in subsection 3.2.
[4]We define agricultural intensification as a more intensive farming system in which more fertilizers (inorganic and organic) and improved seeds are used in order to make smaller farmlands more productive.

Aeronautics and Space Administration-Prediction of Worldwide Energy Resources (NASA-POWER). Because our soil data contain six soil variables–carbon, nitrogen, phosphorus, potassium, calcium, and soil pH, and none of them can in isolation provide an extensive picture of quality of the soil; we use all of them to construct and define the soil quality index. In econometric analysis, we use fixed effects model which helps to control for unobservable household or parcel specific time-invariant characteristics. The results indicate that population pressure reduces soil quality in Kenya. At the same time, however, population pressure is found to have positive effect on agricultural intensification. This implies that farmers are aware of the problem and are trying to reduce its severity. Nonetheless, the fact that we find strong negative impact of population pressure on soil quality suggests that the rate of soil degradation is higher than that of agricultural intensification.

The major contribution of this study is the use of unique panel data that contain actual soil data. Moreover, existing attempts on population pressure and soil erosion/degradation nexus are based on cross-sectional correlation. By using panel data, this study addresses possible endogeneity issues. This is made possible by using fixed effects model which helps to control for unobservable household or parcel specific time-invariant characteristics that may cause bias of parameter estimates by utilizing the panel structure of the data. To the best of our knowledge, this is the first study that rigorously examines the impact of population pressure on soil quality.

The remainder of the paper is organized as follows. Section 2 reviews the literature and provides testable hypotheses. Section 3 discusses the data and descriptive statistics. Identification strategy is discussed in Section 4. Estimation results are discussed in Section 5. The conclusions and policy recommendations are provided in section 6.

2 Literature Review

2.1 Soils as natural capital

To farming households especially in rural SSA, soil is as important as other forms of capital. Its quality not only serves as household wealth, but also increases the value of land (Gray, 2011). Usually soil is represented by a set of biological, physical, and chemical properties. These include primary macro-nutrients including carbon, nitrogen, phosphorus, and potassium; secondary macro-nutrients such as calcium; and chemical properties such as soil pH.

Soil is neither homogeneous across farmlands nor constant over time (Boserup, 1965). It is usually affected by biophysical factors such as climate, biophysical and chemical characteristics of the soil, topography, altitude, temperature, parental material, and biodiversity (Jenny, 1995; Nkonya et al., 2005). These factors influence soil nutrients balances and soil quality in various ways. For example, although rainfall is important for moisture availability which is important for soil health; excessive and intensive rainfall may lead to considerable leaching and depletion of soil nutrients through soil erosion. Drought on the other hand may negatively affect nitrogen-fixation.

In addition, since soil is owned and managed by human being, over time it is also directly or indirectly molded by human activities, amongst other things. For instance, farmers' investment decisions such as conservation practices and application of fertilizers may affect its fertility. Besides the use of fertilizers, other good farming practices that may improve soil quality include fallowing, crop rotation (Tittonell and Giller, 2013), and crop-livestock interaction (Tittonell and Giller, 2013). On the other hand, slash and burning of farm field before cultivation or after harvesting tend to accelerate land degradation and soil nutrient depletion (FAO, 2005; Tittonell and Giller, 2013). One of the socio-economic factors that may affect soil quality is high population pressure unaccompanied by adequate and appropriate use of fertilizers to replenish the soils. In this study, although we discuss most of these factors, our main focus is to examine whether and how population pressure on farmland affects soil fertility.

2.2 Population pressure and soil quality

Like most other countries in SSA, Kenya has high population growth rate.[5] With a population of 49.7 million as of 2017, its population is estimated to be 95.5 million people by 2050 (Population Reference Bureau, 2017). The rate of population growth is likely to be higher in rural areas, thus increasing population pressure on land. Population pressure on farmland can be a fundamental cause of soil degradation.

The main channel through which increasing in population density may affect soil quality is shrinkage in land size which in turn translates into overuse of land. When population density is low, farmland is abundant. As population increases, demand for food also raises which in turn increases demand for farmland. One of the farmers' reactions could be extensification i.e., expansion of agricultural land by bringing new land into cultivation (Grepperud, 1996). However, as population density increases further, it becomes difficult to bring new land into cultivation since little arable land remains unoccupied. Recent empirical studies in SSA indicate that land and farm sizes per smallholder farmer have declined as a result of subdividing land

[5]Its population growth rate is 2.6% almost equivalent to that of SSA as whole (2.7%). Compared to the world average which is 1.18, Kenya's growth rate is high (World Bank, 2016).

across generations (Josephson et al., 2014; Muyanga and Jayne, 2014). Consequently, fallow periods have been shortened (Drechsel et al., 2001; Headey and Jayne, 2014; Otsuka and Place, 2015), and in some places fallow is no longer feasible. At household-level, population pressure could also be reflected by decline in land-labor ratio or per capita owned land, implying land scarcity and overuse of land. Overuse of land unaccompanied by good farming practices could eventually lead to soil fertility decline. The effects are likely to be more harmful in areas where the rate of fertilizer application is very low such that the nutrients being returned to the soil are less than those lost. Also, as population pressure increases, soil fertility is gradually depleted through crop harvest removal, leaching and soil erosion (Ehui and Pender, 2005). A number of existing descriptive studies suggest an inverse relationship between population pressure on farmland and soil fertility (Mortimore, 1993; Mbaga-Semgalawe and Folmer, 2000; Drechsel et al., 2001). However, with exception of the studies by Grepperud (1996), and Shiferaw and Holden (1998);[6] we know of no any rigorous empirical study that has examined this relationship not only in SSA but also in other regions. Grepperud's study on Ethiopia highlands found a positive correlation between population density and soil erosion. Similar association was documented by Shiferaw and Holden (1998) in Ethiopia. Likewise, a descriptive study by Drechsel et al. (2001) found an inverse relationship between population density and soil nutrient balance in 37 countries in SSA, Kenya inclusive. The study's analysis, however, was by scatter plots hence providing only bivariate relationship. One common feature of these studies is that none used data from soil samples.

[6] Grepperud (1996) used soil erosion severity index as a proxy for water erosion; Shiferaw and Holden (1998) used soil erosion perception as outcome variable.

Even though descriptive studies suggest a negative relationship between population pressure and soil fertility, it is worth noting that population pressure on farmland may not necessarily lead to soil degradation. Farmers may react to population pressure by changing their behaviors on farming practices to maintain soil quality. This line of reasoning is well supported by Boserup (1965) and Hayami and Ruttan (1985). Boserup (1965) posits that increase in rural population growth leads to evolution of farming systems. As population density rises and farm sizes decline, traditional practices of soil fertility management such as fallow become difficult, thus causing shifting away from long-fallow periods towards multi-cropping practices. To increase land productivity and crop yield, farmers adopt modern farming technologies such as improved seeds and use of organic and chemical fertilizers.[7] Similarly, the induced innovation theory by Hayami and Ruttan (1985) postulates that as land becomes scarcer due to increase in population density, land-saving technology will be developed to conserve the scarce land and increase use of more abundant resources–labor. This may lead to technological change including use of new farm inputs such as inorganic fertilizers that may increase soil fertility. Recent studies on SSA (Josephson et al.2014; Muyanga and Jayne 2014; Ricker-Gilbert et al. 2014) document a positive relationship between population pressure and agricultural intensification, suggesting that farmers are changing their farming behavior. Indeed, it is rational to believe that when the Boserupian and the induced innovation hypotheses are realized, high population pressure on land

[7]In the literature on integrated soil fertility management, underscored also is importance of intercropping with nitrogen fixing legumes, crop rotation, use of local available technologies of soil management like use of manure or compost and crop residues, and use of modern inputs such as chemical fertilizer. These would not only increase crop yield but also maintain soil fertility. Many of them are complements; none can in isolation meet the requirements of adequate soil fertility management (Sanginga et al., 2003; Marenya and Barrett, 2007; Zingore et al., 2008; Kassie et al., 2012; Tittonell and Giller, 2013; Vanlauwe et al., 2015).

may not hurt the soil; if anything, it may improve it if farmers respond by using modern farming technologies so as to make the small available land more productive.

Deducing from the above, three possible impacts of population pressure on soil quality are: One, if the effects of population pressure on soil degradation dominates the effects of population pressure on intensification, then population pressure culminates into soil degradation. Two, if fertilizer (organic and inorganic) use intensity is higher than the rate of soil degradation, the end result is likely to be increase in soil quality because soil nutrients that are returned to the soil outweigh those lost due to soil degradation. Third, if the rate of intensification is equal to the speed of soil nutrient depletion, then population pressure may have no impact on soil quality. However, in most countries of SSA, fertilizer use intensity is exceedingly low. A number of factors currently impede fertilizer use in the region including limited affordability and accessibility (Vanlauwe et al., 2015), poorly developed supply chains, farmer access to finance, and agricultural crop marketing constraints (Jayne et al., 2019). Also, non-market constraints including lack of technical information on appropriate use of fertilizer and soil degradation tend to reduce the returns of such inputs, thus reduce farmers' incentives to use them (Morris et al. 2007; Marenya and Barrett 2009a ;Marenya and Barrett 2009b). Consequently, for many farmers the rate of fertilizer application is very low and may not be enough to replenish the soil. It is worth noting, however, that unlike many other parts of SSA, parts of Kenya have relatively very high levels of fertilizer use (Sheahan et al., 2013; Tittonell and Giller, 2013; Sheahan and Barrett, 2017). Thus, whether population pressure on farmland deteriorates the quality of the soil is quite an interesting empirical question this study seeks to answer.

From the above literature review, we hypothesize that in an environment characterized by low rates of fertilizer application, population pressure on cropland reduces soil nutrients and soil quality. We use population density and inverse of household owned land per capita to examine the impact of population pressure on soil nutrients and soil quality. Both are regarded as proxies of population pressure on farmland. Second, we expect a positive relationship between population pressure on cropland and agricultural intensification.

3 Data, Soil Quality and Intensification Indices, and Descriptive Statistics

3.1 Data

The data used in this study mainly come from household-level panel surveys collected as part of the Research on Poverty, Environment and Agricultural Technologies (RePEAT) project. The RePEAT surveys are detailed with geo-referenced household-and community-level information. The surveys were conducted jointly by the National Graduate Institute for Policy Studies in Tokyo (GRIPS) and Foundation of Advanced Studies on International Development (FASID). RePEAT questionnaires cover a wide array of information including demographic, household income, education, farm input use, asset ownership, land ownership and land issues, amongst others. The first survey was conducted in 2004. Follow-up survey was conducted in 2012. The 2004 survey covered 899 households randomly selected from 99 sublocations drawn from five provinces of Kenya–Rift Valley, Central, Nyanza, Western, and Eastern. Of this total, only 751 households were successfully traced in 2012, leading to an attrition of 16.5%. We estimate a probit model of 2004-2012 attrition on a number of 2004 household characteristics (Table A1). To control for possible attrition bias, all estimations are weighted by attrition weights estimated based on the methods of inverse probability weights suggested by Fitzgerald et al., (1998) and Wooldridge (2010).

Along with both rounds of surveys, soil samples were collected from the largest maize plot or non-maize cereal plot if the household did not cultivate maize. No soil samples were taken if the household did not cultivate maize or other cereal crops. However, only 2% did not cultivate these crops both in 2004 and 2012. The samples were collected at a depth of 0-20cm at five different positions within each plot and thoroughly mixed (Yamano and Kijima, 2010). Thereafter, they were taken to the soil laboratory at the World Agroforestry Center in Nairobi to analyze their properties (Matsumoto and Yamano, 2009). The samples were tested by a new method developed by Shepherd and Walsh (2002) known as near-infrared reflectance spectroscopy (NIRS) –a method which is particularly appropriate for large sample sizes. In testing the soil samples, NIRS method had several procedures. First, the soils were air-dried and ground to pass through a 2-mm filter, after which they were stored in paper bags at a reasonable room temperature. Then soil properties or attributes were measured for 20% of the total soil samples, designed to sample the variation in the spectral library, and then calibrated to soil reflectance. The resultant calibrations and soil reflectance were then used to predict the soil properties for the entire soil samples. After calibrations an evaluation of prediction performance on predictive and actual observations was done using the coefficient of R^2 and root mean square error. Both tests revealed that the method had high level of prediction accuracy.

Because the soil samples were only collected from maize or non-maize cereal crops, together with the fact that some got spoiled before they were analyzed (Matsumoto and Yamano, 2009); we only have 598 households with soil samples in 2004. In 2012, the samples were collected from 614 out of the 751 traced households. After cleaning, we ended up with a balanced panel data of 480 households from 77 sublocations. Hence the attrition related to soil sampled households is 20%.[8]

In addition to the RePEAT data, we use sublocation-level population density data sourced from the 1989, 1999 and 2009 Kenya Population and Housing Censuses (KNBS, 2010, 2001, 1994). The population census in Kenya is conducted after every ten years and it is detailed to the lowest administrative unit–the village. We also use agroclimatology data namely rainfall, temperature, and wind from National Aeronautics and Space Administration-Prediction of Worldwide Energy Resource (NASA-POWER). NASA through its Earth Science research program collects solar and agroclimatology data by using satellite systems. These satellites and modeled based products are believed to be accurate enough to provide reliable solar and meteorological resource data over regions where surface measurements are scanty or non-existence (Stackhouse et al., 2015). Among others, NASA records daily averaged air temperature (degrees C) at 2 meter above the earth surface, daily wind speed at 10 meter (m/s) above the earth surface, and average precipitation (mm/day). By specifying the Geographical Positioning System (GPS) coordinates one can easily download the data. In the RePEAT surveys sublocation-level latitudes and longitudes were recorded during the surveys. We used these GPS coordinates to merge NASA data with RePEAT data. Since NASA data is recorded on daily basis, before merging it with the RePEAT data, we generated annual variables for five

[8]Table A1 (column 3), we treat those households with missing values of soil samples as attritors. As the table shows, this type of attrition is also not random. As robustness check, we also weighted the regressions by attrition weights estimated from this attrition type. The results (not reported) remained the same.

consecutive years (the survey year and four years before the survey). Subsequently, we calculated five-year average for each of the five variables and use them in the analysis.

3.2 Soil quality index

The soil data are detailed with five soil macro-nutrient variables namely carbon, nitrogen, phosphorus, potassium, and calcium[9], and one chemical property, i.e., soil pH (henceforth, soil variables). However, none of these can in isolation provide an extensive picture of quality of the soil. Therefore, we use all the six soil variables to construct a single soil quality index. We use principal component analysis (PCA). This technique reduces a given number of variables by extracting a linear combination which best describes the variables and transform them into one index (Sena et al., 2002; Gray 2011). PCA determines weights intrinsically and the weights are assigned to each indicator by the relative importance of that factor (SK, 2007). This allows interpretation of better summarized information. The first principal component is constructed in such a way that it captures the greatest variation among the set of variables. It is this first principal component that serves as the index.[10]

Following the literature (Filmer and Pritchett 2001; Gray 2011), we construct the soil quality index as follows:[11]

[9] These soil variables are measured as: percent carbon, percent nitrogen, extractable phosphorus (mg/kg), extractable potassium (cmolc /kg), and extractable calcium (cmolc /kg), respectively.

[10] PCA could result in bias towards weights of indicators which are highly correlated to each other and could give marginal representation to the poorly correlated variables (SK, 2007). Table 3 shows that this is not the case since all our soil variables are strongly correlated.

[11] It is worth noting that soil quality index is likely to be nonlinear. It is difficult however to establish an optimal level because the optimal level is not only crop specific, but also site specific (Ussiri et al., 1998; Be´langer et al., 2000; Srivastava et al., 2006; Musinguzi et al., 2013). Thus, it is not possible to come up with a single minimum or maximum threshold value of the soil quality that can be universally accepted. Nevertheless, existing literature shows that regardless of the type of crop, the desired level of soil carbon content is about 2% (Loveland and Webb,

$$SQ_{it} = \sum_{k=1}^{6} W_k \left[\frac{y_{itk} - y_k}{s_k} \right] \quad (1)$$

where SQI_{it} is the soil quality index of farmland of household i in year t, W_k is the weight of each of the soil variables in the PCA model, and y_{itk} is the soil variable of the farmland of household i in year t. y_k and s_k are the sample mean and standard deviation of variable k, respectively. For robustness check we also construct three other indices: (i) with five soil variables as continuous, and soil pH defined as a dummy equal to one if pH is within a suitable range of 6.6 to 7.3, and zero otherwise;[12] (ii) by using five soil variables (excepting soil pH); and (iii) by using only three key soil variables (nitrogen, phosphorus, and potassium). Estimated factor loadings are reported in appendix Table A2.

3.3 Agricultural intensification index

We also use the PCA to measure farmers' degrees of agricultural intensification. We limit our attention to maize farming intensification. Maize is one of the crops grown by vast majority of the farmers in the study areas.[13] Moreover, it is from maize plots where the soil samples were taken. To create the agricultural intensification index, we use three intensive farming practices-related variables: adoption of improved maize seeds, the amount of chemical fertilizer applied,

2003; Musinguzi et al., 2013). With regards to some specific crops, the optimal phosphorous for corn was found to be 13 mg/kg (Mallarino and Blackmer, 1992), while that of soil carbon content on maize crop was found to be between 1.9% and 2.2% in Uganda (Musinguzi et al., 2016). The optimal level of soil pH on maize crop is widely believed to be 6.0 to 7.0, whereas that of beans is 6.0 to 6.5. Even though it is difficult to establish the optimal soil quality, anecdote evidences suggest that currently in SSA due to soil degradation and low fertilizer usage, soil fertility is far less than the optimal.

[12] Soil pH below 6.6 is acidity and above 7.3 is alkalinity. Both are not suitable for most crops. Thus, an index in which soil pH enters as a continuous variable could wrongly reflect better soil quality.

[13]98% of the sampled households produced maize as one of their crops both in 2004 and 2012.

and the amount of manure applied per hectare of the land cultivated.[14] The index constructed at parcel-level is as follows;

$$AI_{pist} = \sum_{z=1}^{3} W_z \left[\frac{c_{pistz} - c_z}{s_z} \right] \qquad (2)$$

where AI_{pist} is the agricultural intensification of parcel p of household i in season s in year t. W_z is the weight of each of the three intensive farming practiced-related variables used to construct the index, and c_{pistz} is the value of the variable z of household i on parcel p in season s in year t. c_z and s_z are the sample mean and standard deviation of variable z, respectively.

3.4 Descriptive statistics

Table 1 shows the summary statistics for some key variables. While some of the soil nutrients improved over time, the overall soil quality depleted over time. Carbon and nitrogen contents in the soil declined from 2.5 to 2.3; and from 0.22 to 0.18, respectively during the 9 year period. The same declining trend is observed on soil pH from 6.2 in 2004 to 6 in 2012. On the other hand, phosphorus, potassium and calcium increased from 15 to 22.8, from 1.04 to 1.9, and from 7.5 to 9.7, respectively. The overall soil quality declined from 0.10 to 0.03, which indicates soil degradation. During the same period, population density increased from 422.2 in 2004 to 543.5 persons per square kilometer in 2012−an increase of about 29%. Unsurprisingly, owned land per capita declined from 0.37 ha in 2004 to 0.27 in 2012 ha. Similarly, land-labor ratio (household own land divide by the number of household members of working age, i.e., age 15 to 64)

[14]We also use an alternative intensification index constructed by using only two variables more related to soil i.e., the amount of chemical fertilizer applied, and the amount of manure applied per hectare of the land cultivated.

declined from 0.6 to 0.5 during that period. The decrease in both land-labor ratio and owned land per capita, and the increase in population density suggest increasing population pressure on land over time. With regards to agricultural intensification variables, no significant changes are observed between the two survey periods.[15]

Table 1: Summary statistics and *ttest* for equality of means of key variables

	Year=2004		Year=2012			
Variable	Mean	Sd	Mean	Sd	Mean Diff	Sign
Soil quality index	0.10	1.76	0.03	1.78	0.07	
Carbon (%)	2.49	1.45	2.30	0.44	0.19	**
Nitrogen (%)	0.22	0.13	0.18	0.04	0.05	***
Extractable Phosphorus (mg/kg)	15.16	12.31	22.80	34.08	-7.64	***
Extractable Potassium ($cmol_c$ /kg)	1.04	1.86	1.13	0.54	-0.09	
Extractable Calcium ($cmol_c$ /kg	7.48	3.65	9.72	6.48	-2.24	***
Soil pH	6.18	0.59	6.02	0.63	0.16	***
Land-labor ratio	0.59	0.90	0.48	0.66	0.11	**
Land ownership (ha)	2.03	3.25	1.60	2.66	0.43	**
Owned land per capita	0.37	0.60	0.27	0.38	0.10	***
Sublocation population density	422.16	242.29	543.49	337.75	-121.33	***
Inorganic fertilizer use (Kgs/ha)[d]	48.51	113.75	40.09	41.58	8.41	
Quantity of manure use (100Kg/ha)	18.28	38.86	30.04	167.56	-11.76	
% of households used inorganic fertilizer	0.78	0.42	0.77	0.42	0.01	
% households used manure	0.72	0.45	0.72	0.45	0.00	
% of households used fertilizer	0.93	0.26	0.93	0.25	0.00	
1 if improved maize seeds were used[c]	0.51	0.50	0.73	0.44	-0.24	***
1 female headed household	0.22	0.42	0.31	0.46	-0.09	***
Age of household head	56.92	13.39	61.90	13.42	-4.50	***
Years of schooling of household head	6.55	4.71	6.73	4.62	-0.18	
Observations	480		480			

[d]Converted to NPK equivalent. [c] the analysis for this variable is done at plot level; there are 1499 and 1403 observations in 2004 and 2012, respectively.

Table 2 shows the pairwise correlations between population pressure variables and soil variables. Overall, column 1 shows a strong positive correlation between soil macro-nutrients and soil quality index. Similarly, in general the soil variables are strongly correlated to each other. With regards to population pressure and soil variables, a strong inverse relation between

[15]Because the sample is drawn from 5 highly diverse provinces, we also report descriptive statistics by provinces (Table A3).

population density and soil variables is seen. The inverse of per capita owned land is inversely related with soil variables although the correlation is not statistically significant.

Table 2: Pairwise correlations between soil variables and key determinants

	1)	2)	3)	4)	5)	6)	7)	8)	9)
1)SQ	1								
2)Carbon	0.644***	1							
3)Nitrogen	0.515***	0.954***	1						
4)Phosphorus	0.527***	0.138***	-0.012	1					
5)Potassium	0.449***	0.278***	0.180***	0.227***	1				
6)Calcium	0.713***	0.177***	0.059*	0.486***	0.226***	1			
7)soil pH	0.381***	0.251***	-0.321***	0.352***	0.314***	0.538***	1		
8)IOLpc	-0.041	-0.048	-0.049	-0.04	-0.049	-0.019	-0.022	1	
9)Pop	-0.268***	-0.083**	-0.028	-0.227***	-0.147***	-0.110***	-0.265***	0.071**	1

Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. 1) Soil quality index, 8) IOLpc=Inverse of owned land per capita, 9) Pop=Population density

The factor loadings for input use variables are shown in Table 3. The top panel of Table 3 shows the factor loadings at household-level while the bottom panel shows the loadings at parcel-level. At both levels, all the three agricultural intensification variables are positively associated with the intensification index. The intensification index has increased from -0.21 in 2004 to 0.22 in 2012 suggesting that agricultural intensification has improved. And this seems to be driven by increased intensity of manure use among those households using manure and by increase in adoption of improved maize seeds as shown in Table 1.

Table 3: Factor loadings of agricultural intensification

	Year		
	2004	2012	Pooled years
Household-level	Factor loadings		
Individual elements			
Quantity of chemical fertilizer (Kg/Ha)[d]	0.70	0.66	0.65
Quantity of manure (Kg/Ha)	0.21	0.36	0.32
Improved maize seeds (=1)	0.68	0.66	0.67
Proportion of variation explained	0.42	0.43	0.46
Mean of agricultural intensification index	-0.18	0.18	0.00
S.D of agricultural intensification index	1.15	1.12	1.14
Parcel-level			

Individual elements			
Quantity of chemical fertilizer (Kg/Ha)[d]	0.68	0.66	0.65
Quantity of manure (Kg/Ha)	0.29	0.33	0.33
Improved maize seeds (=1)	0.67	0.68	0.67
Proportion of variation explained	0.42	0.45	0.44
Mean of agricultural intensification index	-0.21	0.22	0.00
S.D of agricultural intensification index	1.14	1.11	1.15

[d]Converted to NPK equivalent

Overall, the descriptive statistics suggest that soil quality is declining, but at the same time agricultural intensification is improving. Such intuition provides a basis to perform a rigorous analysis to examine how population pressure on farmland affects soil quality and agricultural intensification.

4 Estimation Strategies

Examining the drivers of the soil quality changes is challenging because measuring changes in soil quality requires a study over a long time horizon since most soil properties are shaped or accumulated after a long period of time. Fortunately, we use a panel data set that span for 9 year-period. This time interval is long enough to analyze the drivers of soil quality. Building on soil formation literature in soil science (Jenny, 1995), an ideal structural equation to estimate the drivers of changes in soil quality or individual properties of the soil can be depicted as follows:

$$SQ_{ijrt} = f(H_{it}, I_{it}, Cl_{jt}, O_{rt}, T_t, P_i, Pop_{jt}, X_{ijrt}) \quad (3)$$

where SQ_{ijrt} is soil quality or a vector of soil properties, $\boldsymbol{H}_{it}$ is a vector of household characteristics, $\boldsymbol{I}_{it}$ is a set of soil conservation variables including application of fertilizers, $\boldsymbol{Cl}_{jt}$ is a set of climate-related variables, $\boldsymbol{O}_{rt}$ is organisms, T_t is time, P_i is parental material, $\boldsymbol{Pop}_{jt}$ is population pressure, $\boldsymbol{X}_{ijrt}$ is a set of other controls. Population pressure on farmlands can affect soil quality in two ways; directly through more frequent and intensive use of farmlands hence soil degradation; and indirectly by inducing smallholder farmers to change their behavior and use more fertilizers to increase land productivity. We therefore estimate two reduced form equations of equation (3). The first estimates the impact of population pressure on soil quality. In the second reduced form, we regress the endogenous variables i.e., fertilizer use variables on population pressure.

4.1 The impact of population pressure on soil quality

To estimate the effect of population pressure on soil quality, we use fixed effects estimation strategy to control for unobservable time-invariant household or parcel specific characteristics that may bias our estimates. Although we use fixed effects, one might suspect that the coefficient of population density might be plagued by endogeneity problem arising from reverse causality. Indeed, it might be the case that it is not population density that is affecting soil quality but rather it is soil quality that is affecting population density since people may tend to settle in areas with fertile soils. To address this concern, we use long lag population density (1989 and 1999). We argue that "current soil quality" (2004 and 2012) cannot affect past population density (1989 and 1999).[16] The model to be estimated is specified as follows.

$$SQ_{ijrt} = \beta_0 + \beta_1 Lsize_{it} + \beta_2 \ln Pop_{jt}^{lag14yrs} + \beta_3 H_{it} + \beta_4 V_{jt} + \gamma_{rt} + \alpha_i + \varepsilon_{ijrt} \quad (4)$$

where i, j,r, t denotes household, sublocation, province, and year of survey, respectively. SQ_{ijrt} is the outcome variable of interest either each of the soil variables or the soil quality index.

[16] However, if current and past population density are highly correlated, the estimates would still suffer from endogeneity problem. The results therefore should be taken as descriptive regression results rather than causal interpretation.

$Lsize_{it}$ is the inverse of per capita owned land. $lnPop_{jt}^{lag14yrs}$ is log of long lag sublocation-level population density (1989 and 1999). H_{it} is a vector of household specific controls namely: a dummy variable equal to 1 if female headed household, age of household head, years of schooling of head of the household, number of male adults and number of female adults (18 years and above), average years of schooling of male adults, average years of schooling of female adults, log of asset value, log of livestock value, and amount of land used other than owned land–rented in land.[17] V_{jt} controls for observable sublocation characteristics including rainfall, temperature, wind, and travel time by car in minutes to the nearest big town. γ_{rt} is expected to capture province-year specific unobservable characteristics such as those in $\boldsymbol{O}_{rt}$ which would affect soil quality. α_i is included to remove the effects of time-invariant household or parcel characteristics such as soil type, parental material, elevation, and soil management ability that may bias our estimates. ε_{ijrt} is the error term that may be heteroskedastic and correlated within a sublocation. We therefore use robust standard errors clustered at the sublocation level (Angrist and Pischke, 2009 chapter 8; Cameron and Miller, 2015 p.14).

4.2 The impact of population pressure on agricultural intensification

Population pressure may also affect soil quality indirectly through its impact on input use. In this section we perform another reduced form analysis of equation (3). Following the literature review, we estimate the impact of population pressure on input use by using four variants of intensification: quantity of manure used per hectare of land cultivated; quantity of chemical

[17]Controlling for this variable is important because if land rental market is functioning and opportunities for renting-in land are there, this may reduce economic and social tension by promoting the movement of land from the land-rich to the land-poor.

fertilizer used per hectare of land cultivated; a dummy variable equal to one if used improved maize seeds; and agricultural intensification index constructed as a linear combination of the first three variables. Formally, we estimate the following model.

$$AI_{pijrt} = \alpha_0 + \alpha_1 Lsize_{it} + \alpha_2 \ln Pop_{jt} + \alpha_3 FS_{pit} + \alpha_4 H_{it} + \alpha_5 V_{jt} + \gamma_{dt} + \xi_i + \mu_{pijrt} \quad (5)$$

where AI_{pijrt} denotes four variants of intensification; quantity of manure, quantity of chemical fertilizer per hectare of land cultivated, a dummy variable equal to one for adoption of improved maize seeds, and the agricultural intensification index. $Lsize_{it}$ is an inverse of owned land size per capita and $lnPop_{jt}$ is log population density. FS_{pit} denotes farm size in hectare. H_{it} is a set of household characteristics defined earlier. V_{jt} controls for observable sublocation-level variables. The division-year fixed effects, $\gamma_{dt,}$ are controlled for by including a set of dummy variables for year of survey and the interactions between years and divisions.[18] These division-year fixed effects are expected to mitigate the possible estimation biases due to unobservables possibly affecting both the outcome and explanatory variables of interest. ξ_i is the fixed effects that controls for unobserved time-invariant household or parcel specific characteristics such as soil type, farm management ability, and farmer's risk preferences that may affect our estimation results. We also include a binary variable to control for season when they are in regression analysis. μ_{pijrt} is the error term. In all regressions the standard errors are clustered at the sublocation.

[18]A division is another type of administrative unit in Kenya. In our data, there are 44 divisions, which are divided into 96 sublocations.

The identifying assumption is that unobservables that might simultaneously affect the outcome variable and our explanatory variables of interest are time-invariant and they will be successfully cancelled out by fixed effects. A concerned for omitted variable bias, however, may remain if the unobservable factors are time-variant. For example, price of inputs, institutional factors such as policies on subsidization of inputs or extension services may be correlated with both population density and adoption of inputs. Failure to control for such factors may result to biased estimates. However, in Kenya input market is well developed and prices are almost the same within the division (Matsumoto and Yamano, 2009). Thus, inclusion of division by time-trends should be able to absorb the impact of prices. Similarly, institutional factors such as policies on subsidization of inputs or extension services are to a large extent countrywide, provincewide, or divisionwide, hence division by time trends should successfully control for such factors.

4.3 Do fertilizers improve soil quality?

So far, we have postulated that population pressure can indirectly affect soil quality by inducing farmers to use more manure, chemical fertilizers, and other inputs so as to make small available farmland more productivity. Implicitly, this should help to replenish the soil nutrients and improve the quality of the soil. It is important however to examine whether intensification actually improves the soil quality. Two approaches can be used. One is to estimate the structural equation and look at the correlation between fertilizer variables and soil quality.[19] Two, is to examine the relationship between the change in soil quality and change in fertilizer use (2004-

[19]The correlation is ambiguous. If it turns out to be positive, it may imply that soil fertility is higher on land where application of fertilizers is higher and if negative it may suggest that people use more inputs on degraded soils.

2012). If it turns out to be positive and significant, we can infer from that as supportive evidence that applying fertilizers indeed improves the soil quality. To examine the later, we use the following model.

$$ChangeinSQ_{ijr} = \alpha_0 + \alpha_1 ChangeinAI_i + \alpha_2 Lsize_i + \alpha_3 \ln Pop_j + \alpha_4 H_i + \alpha_5 V_j + \gamma_r + \mu_{ijr} \qquad (6)$$

Here, $ChangeinSQ_{ijr}$ is the change in soil quality, $ChangeinAI_i$ is the change in agricultural intensification. γ_r is a set of province dummies. Other controls are as defined earlier except that they are now for 2012 year only.

4.4 Current agricultural intensification and past soil quality

It is worth pointing that agricultural intensification can be influenced by past soil fertility. Past soil fertility can affect households' current behavior towards the use of manure, chemical fertilizers and other related inputs in two different ways. First, if past soil was very fertility, there may be no need to use fertilizer inputs in current period. Second, if past soil fertility was very low, households may find it unprofitable (especially in short-run) to use fertilizers in such soils with very low or no fertility. To examine the relationship, we estimate the following model.

$$AI_{ijr} = \alpha_0 + \alpha_1 SQ_i^{2004} + \alpha_2 Lsize_i + \alpha_3 \ln Pop_j + \alpha_4 FS_i + \alpha_5 H_i + \alpha_6 V_j + \gamma_r + \mu_{ijr} \qquad (7)$$

where AI_{ijr}, is agricultural intensification in 2012─hereafter current agricultural intensification. SQ_i^{2004} is soil quality in 2004 (past soil quality). γ_r is a set of province dummies. The remaining controls are as defined before; the difference is that in this setting we only include current period variables.

5 Estimation Results

5.1 Population pressure and soil quality

Table 4 reports the estimation results on the determinants of individual soil macro-nutrients. The inverse of owned land per capita appears to have no significant relationship with soil variables, although it has expected signs in all but soil pH. In column 1, log of past population density significantly reduces carbon content. Similarly, log of past population density negatively affects nitrogen content of the soil (column 2). Likewise, column 3 shows that log past population density leads to reduction in phosphorous. Columns 4 and 5 also show that log past population density reduce potassium and calcium; however, the effect is not statistically significant.

Table 4: Impact of population pressure on soil nutrients

	(1) Carbon	(2) Nitrogen	(3) lnPhosphorus	(4) lnPotassium	(5) lnCalcium	(6) pH	(7) pH dummy
Inverse of owned land per capita	-0.001	-0.0002	-0.0001	-0.001	0.0003	0.001	-0.001
	(-0.574)	(-0.454)	(-0.184)	(-1.041)	(0.064)	(0.986)	(-0.844)
Ln past population density	-0.237**	-0.019**	-0.139**	-0.044	-0.055	0.049	-0.005
	(-2.602)	(-2.306)	(-2.170)	(-0.950)	(-1.505)	(0.957)	(-0.172)
1 if female headed household	0.228	0.019	0.092	0.083	0.134**	0.101	0.046
	(1.339)	(1.165)	(1.433)	(1.462)	(2.275)	(1.336)	(1.042)
Years of education of household head	0.012	0.001	0.014	0.009	0.009	0.007	0.000
	(0.783)	(0.668)	(1.663)	(0.962)	(1.408)	(0.926)	(0.088)
Age of head of household	0.006	0.001	-0.001	0.003	0.001	0.001	0.001
	(0.904)	(0.879)	(-0.207)	(1.600)	(0.568)	(0.540)	(0.423)
Rainfall mm (5 year average)	-0.003	-0.000	0.005	0.002	0.004	0.001	0.001
	(-0.376)	(-0.265)	(0.807)	(0.457)	(1.482)	(0.280)	(0.349)
Temperature °c (5 year average)	-0.001	-0.000*	0.001**	-0.000	0.000	0.000***	0.000
	(-1.468)	(-1.836)	(2.415)	(-0.157)	(0.233)	(2.976)	(0.894)
Wind 10m (m/s) (5 year average)	-0.000	-0.000	-0.000	0.000	-0.001	-0.001	-0.001**
	(-0.230)	(-0.241)	(-0.361)	(0.538)	(-1.381)	(-0.827)	(-2.444)
Constant	13.490*	1.299*	-2.932	-0.037	-5.732*	2.791	-0.086
	(1.880)	(1.906)	(-0.531)	(-0.009)	(-1.832)	(0.613)	(-0.034)
Observations	960	960	960	960	960	960	960
R-squared	0.354	0.418	0.345	0.260	0.358	0.262	0.179
Number of households	480	480	480	480	480	480	480
HH FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Year*Province dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

Robust t-statistics in parentheses. Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are clustered at sublocation-level. Estimates are weighted by attrition weights. In column 7, we use soil pH as a dummy variable equals to one if soil pH >=6.6 & soil pH<=7.3 (neutral) and zero otherwise. Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, per capita value of productive assets, per capita value of nonproductive assets, log value of livestock, log value of land used other than owned land, and log travel time to nearby big town.

Table 5 presents the estimation results of the impact of population pressure on soil quality. The results show that population density reduces soil quality index. Specifically, a percent increase in population density reduces the quality of soil by 0.30 standard deviations (column 3). In columns 1-3 we use soil quality index created by using all the six soil variables. As a robustness check, in column 4 we use soil quality index constructed by using five soil variables (excepting soil pH). The results remain largely unaffected−a percent increase in past population density leads to reduction of soil quality by 0.31 standard deviation. To further check the robustness of our results, in column 5 soil pH enters in the soil quality index as a dummy variable equal to one if neutral (soil pH is within the range of 6.6 to 7.3) and zero otherwise. Again the results remain unaffected. In column 6, we use soil quality index created by using only three soil variables (NPK); the effect of past population density on soil quality remains negative and statistically significant. Surprisingly, the relationship between the inverse of owned land per capita and soil quality index although bears the expected sign, it is not significant. The fact that the inverse of owned land per capita does not enter significantly while population density does, may suggest that within sublocation variation in per capita own land is very small.

Table 5: Impact of population pressure on soil quality

Dependent variable: *Soil quality index*

	(1)	(2)	(3)	(4)	(5)	(6)
Inverse of owned land per capita	-0.002		-0.002	-0.002	-0.002	-0.002
	(-0.595)		(-0.599)	(-0.650)	(-0.552)	(-1.174)
Ln past population density		-0.303**	-0.303**	-0.311**	-0.310**	-0.185**
		(-2.525)	(-2.520)	(-2.595)	(-2.591)	(-2.035)
1 if female headed household	0.402*	0.425*	0.429*	0.405*	0.393*	0.256**
	(1.822)	(1.975)	(1.987)	(1.865)	(1.799)	(2.429)
Years of education of head of household	0.024	0.028	0.028	0.025	0.025	0.021
	(1.045)	(1.264)	(1.270)	(1.159)	(1.124)	(1.248)

Age of head of household	0.011	0.010	0.010	0.010	0.010	0.007
	(1.391)	(1.256)	(1.253)	(1.206)	(1.180)	(1.655)
Rainfall mm (5 year average)	-0.001	0.008	0.008	0.006	0.006	0.012
	(-0.049)	(0.647)	(0.656)	(0.528)	(0.484)	(1.515)
Temperature °c (5 year average)	-0.000	-0.001	-0.001	-0.001	-0.001	-0.000
	(-0.703)	(-1.195)	(-1.198)	(-1.388)	(-1.459)	(-1.476)
Wind 10m (m/s) (5 year average)	-0.002	-0.000	-0.000	-0.000	-0.000	0.001
	(-0.597)	(-0.138)	(-0.135)	(-0.099)	(-0.019)	(0.660)
Constant	1.080	-0.204	-0.327	2.496	3.301	-6.911
	(0.095)	(-0.020)	(-0.032)	(0.247)	(0.330)	(-0.923)
Observations	960	960	960	960	960	960
R-squared	0.165	0.198	0.198	0.236	0.252	0.092
Number of households	480	480	480	480	480	480
HH FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Year*Province dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

Robust t-statistics in parentheses. Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are clustered at sublocation level. Estimates are weighted by attrition weights. In columns 1-3 soil quality index is created by using all six soil variables. In column (4) soil quality index is created by using five macro-nutrients (excluding soil pH). In column (5) soil quality index by using six soil variables but soil pH enters as a dummy variable i.e. 1 if neutral (soil pH >=6.6 & soil pH<=7.3) and zero otherwise. In column (6) soil quality index is created by using nitrogen, phosphorus, and potassium (NPK)-key soil macro-nutrients. Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, per capita value of productive assets, per capita value of nonproductive assets, log value of livestock, log value of land used other than owned land, and log travel time to nearby big town.

5.2 Population pressure and agricultural intensification

Table 6 shows the estimation results on the determinants of agricultural intensification. The results show that log of inverse of owned land per capita is positively associated with all measures of agricultural intensification but the relationship is only significant on chemical fertilizer use (column 2) and agricultural intensification index (Columns 5 and 6). Similarly, the expected positive effect of population density on measures of intensification is found. A percent increase in population density increases the intensification by 0.33 standard deviations (column 5). In addition, population density appears to affect agricultural intensification in terms of use of chemical fertilizers (column 3), and adoption of improved maize seeds (column 4). The effect of population density on manure use is positive but not statistically significant (column 1).

Table 6: Impact of population pressure on agricultural intensification

	(1) Manure (t/ha)	(2) Chemical (10kg/ha)	(3) ln Chemical (10kg/ha)	(4) Maizehyv (=1)	(5) Intens. index	(6) Intens. Index2
Log inverse of owned land per capita	0.325	0.513*	0.116	0.014	0.128*	0.155**
	(1.522)	(1.780)	(1.217)	(0.582)	(1.934)	(2.274)
Log population density	0.845	0.321	0.616**	0.132*	0.329**	0.258
	(1.437)	(0.529)	(2.441)	(1.770)	(2.280)	(1.621)
Cultivated plot size (ha)	-0.888***	-1.550***	-0.173	0.041	-0.260***	-0.445***
	(-3.859)	(-3.526)	(-0.974)	(1.157)	(-3.083)	(-5.264)
1 if female headed household	-0.425	-0.626	-0.243	0.058	-0.056	-0.196*
	(-1.656)	(-1.063)	(-1.059)	(1.161)	(-0.427)	(-1.689)
Age of household head	-0.000	0.019	0.015**	-0.001	0.001	0.003
	(-0.033)	(1.124)	(2.151)	(-0.485)	(0.344)	(0.706)
Years of education of household head	0.038	-0.024	0.027	0.003	0.005	0.006
	(1.019)	(-0.349)	(1.115)	(0.382)	(0.378)	(0.444)
Constant	0.935	8.787	4.125	-0.644	-1.176	0.583
	(0.093)	(0.788)	(0.693)	(-0.374)	(-0.349)	(0.196)
Observations	2,851	2,851	2,851	2,851	2,851	2,851
R-squared	0.079	0.118	0.101	0.209	0.187	0.120
Number of pid	1,184	1,184	1,184	1,184	1,184	1,184
HH FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
pid FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Year*Division	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

Robust t-statistics in parentheses; Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are clustered at sublocation level. Estimates are weighted by attrition weights. In column (5) agricultural intensification index is created by using three intensification variables. In column (6) index created by using two intensification variables (excluding improved maize adoption). Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, Log value of assets, log value of livestock, log value of land used other than owned land, and log travel time to nearby big town.

5.3 Does the use of fertilizers improve soil quality?

Table 7 reports the correlation between change in fertilizer variables and change in soil quality. There is a significant and positive relationship between change chemical fertilizer and change in soil quality. Likewise, the change in agricultural intensification and change in soil quality are significantly and positively related.

Table 7: Correlation between change in agricultural intensification and change in soil quality
Dependent variable: *Change in soil quality index (2004-2012)*

	(1)	(2)	(3)	(4)
Change in Manure (t/ha) (2004-2012)	-0.000			
	(-0.015)			
Change in Chemical fertilizer (10kg/ha) (2004-2012)		0.076**		
		(2.331)		
Change in ln Chemical (10kg/ha) (2004-2012)			0.018*	
			(1.900)	
Change in agricultural intensification index‡ (2004-2012)				0.066*
				(1.718)
Ln inverse of owned land per capita	-0.009	-0.009	-0.012	-0.007
	(-0.137)	(-0.141)	(-0.193)	(-0.107)
Ln population density	0.352***	0.333***	0.336***	0.347***
	(2.759)	(2.701)	(2.683)	(2.750)
1 if female headed household	0.105	0.068	0.114	0.107
	(0.949)	(0.671)	(1.067)	(0.986)
Years of education of household head	-0.016	-0.018	-0.015	-0.015
	(-0.941)	(-1.104)	(-0.919)	(-0.907)
Age of head of household	-0.004	-0.004	-0.004	-0.004
	(-0.639)	(-0.584)	(-0.605)	(-0.626)
Rainfall mm (5 year average)	-0.030***	-0.028***	-0.028***	-0.029***
	(-5.028)	(-4.873)	(-4.687)	(-4.873)
Temperature (5 year average)	0.000*	0.000	0.000	0.000
	(1.709)	(1.457)	(1.619)	(1.615)
Wind (5 year average)	-0.023***	-0.022***	-0.022***	-0.022***
	(-5.184)	(-5.068)	(-4.890)	(-5.031)
Constant	65.784***	62.271***	62.500***	63.893***
	(4.745)	(4.652)	(4.460)	(4.602)
Observations	480	480	480	480
R-squared	0.360	0.374	0.367	0.363
Province dummies	*Yes*	*Yes*	*Yes*	*Yes*

Robust t-statistics in parentheses; ***Significant at 1% level, **Significant at 5%, *Significant at 10%. Robust standard errors are clustered at sublocation level. ‡The intensification index is created by using Manure and Chemical fertilizer. Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, per capita value of productive assets, per capita value of nonproductive assets, log value of livestock, log value of land used other than owned land, log travel time to nearby big town.

Table 8 shows the relationship between soil fertility and agricultural intensification. As expected, all our agricultural intensification measures−manure use, chemical fertilizer application, and agricultural intensification index are positively associated with soil fertility. However, for manure the relationship is not significant. Overall, however, the results provide supportive evidence that the use of fertilizers do indeed increase the quality of the soil. We also report results for separate indicators of soil quality in Table A5.

Table 8: Correlation between agricultural intensification and soil quality
Dependent variable: *Soil quality index*

	(1)	(2)	(3)	(4)	(5)	(6)
Manure (t/ha)	0.001		0.002	0.002		
	(0.336)		(1.278)	(1.278)		
Chemical fertilizer (10kg/ha)		0.047***	0.051***	0.051***		
		(3.134)	(3.102)	(3.102)		
Manure (t/ha)* Chemical fertilizer (10kg/ha)				-0.002***		
				(-2.856)		
Ag intensification index					0.194***	
					(3.093)	
Ag intensification index‡						0.163*
						(1.893)
Inverse of owned land per capita	-0.001	-0.002	-0.002	-0.002	-0.002	-0.002
	(-0.474)	(-0.852)	(-0.815)	(-0.815)	(-0.855)	(-0.643)
Ln population density	-0.258**	-0.222**	-0.227**	-0.227**	-0.227**	-0.241**
	(-2.437)	(-2.432)	(-2.508)	(-2.508)	(-2.390)	(-2.475)
1 if female headed household	0.427*	0.332*	0.326*	0.326*	0.363*	0.387*
	(1.951)	(1.794)	(1.806)	(1.806)	(1.767)	(1.922)
Years of education of household head	0.027	0.022	0.022	0.022	0.024	0.022
	(1.207)	(1.017)	(1.021)	(1.021)	(1.043)	(0.980)
Age of household head	0.012	0.010	0.010	0.010	0.011	0.011
	(1.462)	(1.358)	(1.339)	(1.339)	(1.456)	(1.376)
Rainfall mm (5 year average)	0.008	0.010	0.010	0.010	0.010	0.009
	(0.654)	(0.962)	(1.020)	(1.020)	(0.927)	(0.812)
Temperature (5 year average)	-0.001	-0.000	-0.000	-0.000	-0.000	-0.000
	(-1.014)	(-0.995)	(-0.965)	(-0.965)	(-1.026)	(-0.881)
Wind (5 year average)	-0.000	0.000	0.000	0.000	0.000	0.000
	(-0.085)	(0.069)	(0.098)	(0.098)	(0.024)	(0.001)
Constant	-2.032	-3.886	-4.340	-4.340	-4.671	-3.906
	(-0.194)	(-0.433)	(-0.494)	(-0.494)	(-0.487)	(-0.403)
Observations	960	960	960	960	960	960
R-squared	0.172	0.218	0.223	0.223	0.197	0.193
Number of households	480	480	480	480	480	480
HH FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Year*Province dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

Robust t-statistics in parentheses. Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are clustered at sublocation level. Estimates are weighted by attrition weights. ‡The intensification index is created by using Manure and Chemical fertilizer. Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, per capita value of productive assets, per capita value of nonproductive assets, log value of livestock, log value of land used other than owned land, log travel time to nearby big town.

5.4 Current agricultural intensification and past soil quality

Table 9 shows the correlation between current agricultural intensification and past soil fertility in Uganda. There is positive relationship between current application of agricultural intensification and past soil quality. Specifically, this relationship is statistically significant for chemical fertilizer application and agricultural intensification index. The results suggest that farmers tend to use chemical fertilizers on fertile land. The results are in line with earlier studies that have shown that chemical fertilizers are less effective on soils with low soil fertility (Marenya and Barrett, 2009b, 2009a). It is further interesting to note that the square term of past soil quality is significantly and negatively correlated with current agricultural intensification. This suggests that when the soil is very fertile farmers have no reason to use chemical fertilizers.

Table 9: Correlation between past soil fertility and current agricultural intensification

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Manure (t/ha)		ln Chemical fertilizer (10kg/ha)		Chemical fertilizer (10kg/ha)		Agricultural int. index‡	
Inverse of owned land per capita	0.029**	0.028**	0.006	0.005	0.040	0.034	0.006	0.006
	(2.008)	(1.996)	(0.787)	(0.634)	(0.928)	(0.819)	(1.112)	(1.018)
Ln population density	0.463**	0.419**	0.972***	0.926***	0.832	0.599	0.127*	0.096
	(2.538)	(2.395)	(4.067)	(3.782)	(1.378)	(0.922)	(1.756)	(1.237)
Past soil quality (in 2004)	0.067	0.183	0.275***	0.397***	1.034***	1.652***	0.128***	0.208***
	(1.194)	(1.606)	(3.788)	(3.522)	(3.944)	(3.854)	(4.019)	(4.070)
Past soil quality (in 2004) squared		-0.029		-0.031		-0.154*		-0.020**
		(-1.477)		(-1.340)		(-1.923)		(-2.054)
Area cultivated (ha)	-0.213**	-0.222**	0.003	-0.007	-0.517*	-0.566*	-0.074**	-0.081**
	(-2.087)	(-2.188)	(0.033)	(-0.067)	(-1.841)	(-1.968)	(-2.055)	(-2.220)
1 if female headed household	-0.512**	-0.482**	-0.221	-0.190	0.060	0.220	-0.023	-0.002
	(-2.379)	(-2.304)	(-0.954)	(-0.805)	(0.045)	(0.166)	(-0.141)	(-0.012)
Age of head of household	-0.001	-0.002	-0.004	-0.006	-0.026	-0.033	-0.003	-0.004
	(-0.060)	(-0.211)	(-0.492)	(-0.674)	(-0.989)	(-1.254)	(-0.974)	(-1.250)
Years of education of household head	-0.014	-0.015	-0.021	-0.021	-0.041	-0.043	-0.006	-0.006
	(-0.325)	(-0.335)	(-0.699)	(-0.714)	(-0.418)	(-0.452)	(-0.464)	(-0.499)
Constant	-5.769**	-5.705**	-13.85***	-13.79***	-21.78***	-21.44***	-3.559***	-3.515***
	(-2.330)	(-2.316)	(-6.409)	(-6.407)	(-4.069)	(-3.949)	(-4.972)	(-4.846)
Observations	480	480	480	480	480	480	480	480
R-squared	0.198	0.200	0.302	0.307	0.172	0.181	0.195	0.205
Province dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

Robust t-statistics in parentheses. Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are clustered at sublocation-level. ‡The intensification index is created by using Manure and Chemical fertilizer. Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, log value of assets, log value of livestock, log value of land used other than owned land, and log travel time to nearby big town.

6 Conclusion and policy implications

By using a unique panel data with real soil samples from rural households in Kenya, this paper sought to examine two things—the impact of population pressure on soil quality and the effect of population pressure on agricultural intensification. We find that population density significantly reduces soil quality. The results are robust to alternative specification and alternative measures of soil quality index. However, the inverse of owned land per capita (another proxy for land constraint) does not appear to have any significant negative effect on soil quality. This result is a bit surprising, but may suggest that within sublocation variation is small. We also find significant positive effects of inverse of owned land per capita and population density on agricultural intensification. These results are interesting and indicate farmers' positive response to cope with declining soil fertility. Indeed, this suggests that the negative effect of population pressure on soil quality may have been worse than what we find here if farmers were not responding to mitigate the problem as shown by the positive effect of population pressure on agricultural intensification. However, the fact that we find significant positive effect of population pressure on agricultural intensification on one hand, and significant negative effect of population pressure on soil fertility on the other hand, suggests that the rate at which soil degradation is taking place is higher than the speed of intensification. Overall, the results support the population hypothesis and indicate that in areas that this study covers, the Boserupian hypothesis is yet to materialize at a desired rate. Thus, it could be interesting if future studies could look at the same issue in other regions with possibly completely different farming system.

To promote agricultural intensification such that the effect of population density on intensification outweighs that of population density on soil degradation, good policies to stimulate investment in soil improvement are encouraged. Specifically, policies that can make it easier for farmers to use external inputs to replenish the soil fertility. Besides promoting the use of external inputs, farmers should be encouraged to use the locally available inputs including manure. Also polices that can ultimately lead to improved markets of agricultural products may induce farmers to invest in soil improvement. Without such policies, farmers are not likely to invest in soil improvement as long as what they produce from such degrading lands can meet their immediate consumption. Lastly, family planning especially among rural households should also be encouraged.

Even though this paper shows that population pressure reduces soil quality, a remaining question is what is its welfare impact? Although this is beyond the scope of this study, it is worth pointing out that the welfare impact is ambiguous. It may be negative since reduction in soil quality may translates into lower land productivity and crop income. In addition, scarcity of land resulting from population could increase liquidity constraints and reduce households' ability to engage in off-farm activities through for example establishing small scale businesses. On the other hand, high population may stimulate the rise of opportunities in the off-farm sector. For example, high population can increase demand for goods and services from non-agricultural sector. This may lead to concentration of small scale industries which may create off-farm jobs and increase incomes of the rural households. Moreover, individuals from land constrained communities may have more incentive to migrate and seek jobs in urban areas and in turn send remittances to their households. High population may also increase agricultural productivity by increasing demand for agricultural commodities and decrease wage rates for agricultural labor. Thus, to understand the impact of population pressure on rural households' welfare, one needs to examine its impact on shares of income and total income—an issue reserved for future study.

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Appendices

Table A1: Determinants of attrition in the household survey and soil samples

	(1)	(2)	(3)
Dependent variable	att1	att2	att3
Household characteristics in 2004			
Household head's age	-0.006	0.006	0.003
	(0.006)	(0.008)	(0.006)
Household head's education	-0.022	0.043	0.015
	(0.010)	(0.032)	(0.021)
1 if household head is female	0.262*	0.033	0.249*
	(0.152)	(0.241)	(0.147)
Number of female adults	-0.110	-0.045	-0.087
	(0.078)	(0.094)	(0.075)
Number of male adults	-0.026	-0.029	-0.049
	(0.061)	(0.103)	(0.061)
Average years of schooling of female adults	0.001	-0.022	0.028
	(0.021)	(0.033)	(0.021)
Average years of schooling of male adults	-0.003	-0.009	-0.007
	(0.022)	(0.027)	(0.021)
Log of value of assets (Kshs)	-0.011	0.017	0.010
	(0.050)	(0.0744)	(0.054)
Log of land holdings (ha)	-0.013	-0.152	-0.053
	(0.0547)	(0.094)	(0.064)
Region dummies§			
Western	0.933***	1.323***	0.504
	(0.228)	(0.335)	(0.324)
Rift Valley	0.072	0.049	-0.726**
	(0.206)	(0.363)	(0.308)
Central	0.157	0.134	-0.572*
	(0.226)	(0.324)	(0.295)
Eastern	-0.151	0.333	-0.712**
	(0.248)	(0.420)	(0.305)
Constant	-0.432	-2.323***	-0.391
	(0.549)	(0.860)	(0.659)
Number of households	899	899	598

Robust standard errors are in parentheses. Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. att1: 1 if not interviewed in second survey, att2: 1 if no soil sample in the first survey. att3: 1 if soil sample available in the first survey but household not available in the second survey or available but soil sample not available. §Reference category is Nyanza province.

Table A2: Factor loadings of soil quality index

	Year		
	2004	2012	Pooled years
	Factor loadings		
Individual elements			
Carbon (%)	0.59	0.11	0.60
Nitrogen (%)	0.58	-0.16	0.53
Extractable Phosphorus (mg/kg)	0.34	0.43	0.30
Extractable Potassium (cmolc /kg)	0.22	0.51	0.37
Extractable Calcium (cmolc /kg)	0.38	0.53	0.35
Soil pH	-0.11	0.49	0.08
Proportion of variation explained	0.42	0.49	0.36
Mean of soil quality index	0.07	-0.07	0.00
S.D of soil quality index	1.8	1.00	1.5

Table A3: Descriptive statistics by 5 provinces

Variable	Year =2004 Mean	Sd	Year=2012 Mean	Sd	Mean Diff	Sign.
Nyanza						
Soil quality index	0.22	1.36	0.11	1.38	0.11	
Carbon (%)	2.34	0.96	2.27	0.32	0.07	
Nitrogen (%)	0.23	0.10	0.18	0.02	0.05	***
Extractable Phosphorus (mg/kg)	19.04	23.29	19.72	14.94	-0.68	
Extractable Potassium ($cmol_c$ /kg)	0.86	0.60	0.89	0.34	-0.04	
Extractable Calcium ($cmol_c$ /kg	9.80	7.47	11.34	9.09	-1.54	
Soil pH	6.37	0.61	6.16	0.60	0.21	**
Land-labor ratio	0.56	0.81	0.46	0.45	0.10	
Land ownership (ha)	1.81	1.90	1.53	1.40	0.28	
Owned land per capita	0.30	0.37	0.23	0.20	0.07	
Sublocation population density	427.32	223.47	556.85	259.62	-129.53	***
Inorganic fertilizer use (Kgs/ha)[d]	21.20	35.73	30.33	39.10	-9.13	
Quantity of manure use (100Kg/ha)	495.32	990.55	741.23	1808.85	-245.91	
% of households used inorganic fertilizer	0.58	0.50	0.61	0.49	-0.03	
% households used manure	0.73	0.45	0.54	0.50	0.19	**
% of households used fertilizer	0.90	0.31	0.85	0.36	0.05	
1 if improved maize seeds were used [c]	0.53	0.50	0.64	0.48	-0.11	***
Observations	59		59			
Western						
Soil quality index	-1.98	0.58	-1.47	0.70	-0.51	***
Carbon (%)	1.32	0.37	2.17	0.22	-0.85	***
Nitrogen (%)	0.12	0.04	0.17	0.02	-0.05	***
Extractable Phosphorus (mg/kg)	9.27	2.03	13.62	4.09	-4.36	***
Extractable Potassium ($cmol_c$ /kg)	0.39	0.16	0.58	0.18	-0.19	***
Extractable Calcium ($cmol_c$ /kg	3.81	1.04	4.37	1.37	-0.56	***
Soil pH	6.02	0.22	5.56	0.41	0.46	***
Land-labor ratio	0.30	0.29	0.18	0.15	0.12	***
Land ownership (ha)	1.26	1.07	0.89	0.85	0.37	**
Owned land per capita	0.15	0.13	0.10	0.09	0.05	***
Sublocation population density	604.54	224.00	578.99	358.03	25.55	
Inorganic fertilizer use (Kgs/ha)[d]	65.67	57.66	57.16	48.16	8.51	
Quantity of manure use (100Kg/ha)	790.13	1301.04	1364.46	1868.63	-574.32	*
% of households used inorganic fertilizer	0.86	0.35	0.84	0.37	0.02	
% households used manure	0.64	0.49	0.74	0.44	-0.10	
% of households used fertilizer	0.96	0.20	0.98	0.14	-0.02	
1 if improved maize seeds were used [c]	0.46	0.50	0.63	0.48	-0.17	***
Observations	51		51			
Rift Valley						
Soil quality index	1.17	1.48	1.61	1.36	-0.44	***
Carbon (%)	2.99	1.30	2. 2	0.41	0.57	***
Nitrogen (%)	0.25	0.11	0.17	0.02	0.08	***
Extractable Phosphorus (mg/kg)	22.04	13.14	44.98	56.56	-22.94	***
Extractable Potassium ($cmol_c$ /kg)	1.82	3.34	1.60	0.55	0.22	
Extractable Calcium ($cmol_c$ /kg	8.24	1.90	14.01	5.45	-5.77	***
Soil pH	6.30	0.67	6.35	0.50	-0.05	
Land-labor ratio	0.93	1.36	0.72	1.15	0.22	
Land ownership (ha)	3.22	5.56	2.61	4.49	0.61	

Owned land per capita	0.54	0.81	0.40	0.54	0.14	
Sublocation population density	214.10	162.24	433.75	348.25	-219.65	***
Inorganic fertilizer use (Kgs/ha)[d]	60.57	193.72	40.10	33.68	20.47	
Quantity of manure use (100Kg/ha)	977.06	4812.09	1271.23	2807.43	-294.17	
% of households used inorganic fertilizer	0.72	0.45	0.78	0.42	-0.05	
% households used manure	0.44	0.50	0.52	0.50	-0.08	
% of households used fertilizer	0.86	0.35	0.90	0.31	-0.04	
1 if improved maize seeds were used [c]	0.63	0.48	0.85	0.35	-0.22	***
Observations	134		134			
Central						
Soil quality index	0.40	1.51	-0.58	1.68	0.97	***
Carbon (%)	2.84	1.56	2.36	0.50	0.48	***
Nitrogen (%)	0.27	0.14	0.20	0.05	0.07	***
Extractable Phosphorus (mg/kg)	11.90	5.28	11.94	10.37	-0.04	
Extractable Potassium ($cmol_c$ /kg)	0.86	0.29	1.13	0.38	-0.27	***
Extractable Calcium ($cmol_c$ /kg	7.74	2.26	8.52	5.57	-0.78	*
Soil pH	5.91	0.40	5.81	0.66	0.10	*
Land-labor ratio	0.48	0.61	0.45	0.76	0.03	
Land ownership (ha)	1.54	1.71	1.19	1.31	0.35	***
Owned land per capita	0.36	0.60	0.26	0.35	0.10	**
Sublocation population density	533.00	194.31	610.97	344.23	-77.97	***
Inorganic fertilizer use (Kgs/ha)[d]	53.72	66.25	42.73	45.99	10.99	*
Quantity of manure use (100Kg/ha)	3296.99	4175.49	5822.74	26599.05	-2525.75	
% of households used inorganic fertilizer	0.89	0.31	0.82	0.39	0.08	**
% households used manure	0.90	0.30	0.88	0.33	0.02	
% of households used fertilizer	0.98	0.13	0.97	0.18	0.02	
1 if improved maize seeds were used [c]	0.62	0.49	0.79	0.41	-0.17	***
Observations	185		185			
Eastern						
Soil quality index	-2.01	0.53	-0.53	1.12	-1.48	***
Carbon (%)	1.08	0.25	1.85	0.21	-0.77	***
Nitrogen (%)	0.09	0.02	0.15	0.02	-0.05	***
Extractable Phosphorus (mg/kg)	10.01	2.88	16.84	7.50	-6.83	***
Extractable Potassium ($cmol_c$ /kg)	0.46	0.14	0.67	0.31	-0.20	***
Extractable Calcium ($cmol_c$ /kg	5.43	2.72	6.31	3.53	-0.88	
Soil pH	6.83	0.48	6.27	0.34	0.56	***
Land-labor ratio	0.45	0.46	0.31	0.27	0.14	**
Land ownership (ha)	1.75	1.69	1.22	0.95	0.53	**
Owned land per capita	0.26	0.26	0.21	0.17	0.06	
Sublocation population density	384.57	223.06	513.18	223.39	-128.61	***
Inorganic fertilizer use (Kgs/ha)[d]	13.61	17.09	25.87	32.45	-12.26	***
Quantity of manure use (100Kg/ha)	1325.73	1655.60	1613.23	3069.51	-287.50	
% of households used inorganic fertilizer	0.69	0.47	0.75	0.44	-0.06	
% households used manure	0.86	0.35	0.86	0.35	0.00	
% of households used fertilizer	0.92	0.27	0.96	0.20	-0.04	
1 if improved maize seeds were used [c]	0.07	0.26	0.65	0.48	-0.58	***
Observations	51		51			

Table A5: The correlation between agricultural intensification and individual nutrient indicators

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Carbon		Nitrogen		Ln phosphorus	
Manure (t/ha)	0.002**	0.003***	0.000	0.000*	-0.002***	-0.002***
	(2.035)	(3.007)	(0.906)	(1.953)	(-3.973)	(-3.257)
Chemical fertilizer (10kg/ha)	0.035***	0.039***	0.003***	0.004***	0.008**	0.009**
	(3.211)	(3.170)	(2.997)	(2.917)	(2.230)	(2.331)
Manure (t/ha)* Chemical fertilizer (10kg/ha)		-0.001***		-0.000**		-0.000
		(-2.892)		(-2.110)		(-0.784)
Inverse of owned land per capita	-0.002	-0.002	-0.000	-0.000	-0.001	-0.001
	(-0.906)	(-0.879)	(-0.730)	(-0.711)	(-0.400)	(-0.393)
Ln population density	-0.141*	-0.145*	-0.011	-0.012	-0.120**	-0.121**
	(-1.866)	(-1.922)	(-1.576)	(-1.627)	(-2.029)	(-2.031)
1 if female headed household	0.146	0.141	0.011	0.011	0.071	0.070
	(1.003)	(0.996)	(0.791)	(0.781)	(1.161)	(1.147)
Years of education of household head	0.006	0.006	0.001	0.001	0.013	0.013
	(0.376)	(0.382)	(0.346)	(0.350)	(1.556)	(1.556)
Age of household head	0.005	0.005	0.000	0.000	-0.001	-0.001
	(0.942)	(0.924)	(0.850)	(0.837)	(-0.211)	(-0.220)
Rainfall mm (5 year average)	-0.003	-0.003	-0.000	-0.000	0.005	0.005
	(-0.447)	(-0.413)	(-0.294)	(-0.257)	(0.839)	(0.847)
Temperature (5 year average)	-0.000	-0.000	-0.000*	-0.000*	0.001**	0.001**
	(-1.270)	(-1.244)	(-1.736)	(-1.711)	(2.466)	(2.475)
Wind (5 year average)	-0.000	-0.000	-0.000	-0.000	-0.000	-0.000
	(-0.074)	(-0.048)	(-0.118)	(-0.096)	(-0.312)	(-0.305)
Constant	11.714*	11.390*	1.152*	1.124*	-3.672	-3.733
	(1.909)	(1.910)	(1.970)	(1.977)	(-0.647)	(-0.656)
Observations	960	960	960	960	960	960
R-squared	0.387	0.391	0.447	0.450	0.346	0.347
Number of households	480	480	480	480	480	480
HH FE	Yes	Yes	Yes	Yes	Yes	Yes
Year*Province dummies	Yes	Yes	Yes	Yes	Yes	Yes

Robust t-statistics in parentheses. Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are clustered at sublocation-level. Estimates are weighted by attrition weights. Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, per capita value of productive assets, per capita value of nonproductive assets, log value of livestock, log value of land used other than owned land, and log travel time to nearby big town.

Table A5 cont.: The correlation between agricultural intensification and individual nutrient indicators.

	(1)	(2)	(3)	(4)	(5)	(6)
Variables	Ln potassium		Ln Calcium		Soil pH	
Manure (t/ha)	-0.001	-0.000		-0.001***	-0.003***	-0.003***
	(-1.363)	(-0.859)		(-3.282)	(-4.371)	(-4.103)
Chemical fertilizer (10kg/ha)	0.006*	0.007**	0.008**	0.009**	0.000	0.000
	(1.964)	(2.231)	(2.008)	(2.209)	(0.021)	(0.071)
Manure (t/ha)* Chemical fertilizer (10kg/ha)		-0.000*		-0.000***		-0.000
		(-1.983)		(-2.922)		(-0.389)
Inverse of owned land per capita	-0.001	-0.001	0.000	0.000	0.002	0.002
	(-1.311)	(-1.275)	(0.353)	(0.363)	(1.283)	(1.283)
Ln population density	-0.025	-0.026	-0.066*	-0.067*	0.046	0.046
	(-0.575)	(-0.599)	(-1.893)	(-1.934)	(0.916)	(0.910)
1 if female headed household	0.070	0.069	0.113*	0.111*	0.097	0.097
	(1.214)	(1.196)	(1.984)	(1.966)	(1.328)	(1.329)
Years of education of household head	0.008	0.008	0.009	0.009	0.008	0.008
	(0.876)	(0.876)	(1.372)	(1.373)	(1.091)	(1.092)
Age of household head	0.003	0.003	0.001	0.001	0.002	0.002
	(1.659)	(1.637)	(0.702)	(0.674)	(0.678)	(0.675)
Rainfall mm (5 year average)	0.002	0.002	0.005*	0.005*	0.001	0.001
	(0.489)	(0.514)	(1.757)	(1.805)	(0.276)	(0.280)
Temperature (5 year average)	-0.000	-0.000	0.000	0.000	0.000***	0.000***
	(-0.060)	(-0.041)	(0.209)	(0.228)	(2.878)	(2.877)
Wind (5 year average)	0.000	0.000	-0.001	-0.001	-0.001	-0.001
	(0.656)	(0.677)	(-1.093)	(-1.072)	(-0.716)	(-0.711)
Constant	-0.386	-0.473	-6.102**	-6.229**	3.092	3.069
	(-0.100)	(-0.123)	(-2.016)	(-2.059)	(0.701)	(0.693)
Observations	960	960	960	960	960	960
R-squared	0.270	0.271	0.374	0.377	0.264	0.264
Number of households	480	480	480	480	480	480
HH FE	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*
Year*Province dummies	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*	*Yes*

Robust t-statistics in parentheses. Asterisks ***, ** and * represent significance at the 1%, 5%, and 10% levels, respectively. Robust standard errors are clustered at sublocation-level. Estimates are weighted by attrition weights. Additional controls include family size, number of male adults, number of female adults, average years of schooling of male adults, average years of schooling of female adults, per capita value of productive assets, per capita value of nonproductive assets, log value of livestock, log value of land used other than owned land, log travel time to nearby big town.