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Effects of rising rural population density on smallholder agriculture in Kenya

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ABSTRACT

This study measures how Kenyan farmers and farming systems have responded to changes in population density and associated land pressures. Kenya is a relatively densely populated area, with 40% of its rural people residing on 5% of its rural land. We develop a structural model for estimating the impact of population density on input and output prices, farm size, and ultimately on smallholder behavior and agricultural intensification. Evidence is derived from a five-round panel survey between 1997 and 2010. We find a negative relationship between localized population density and farm size, and a positive relationship between population density and measures of land intensification up to roughly 500 persons/km^2. Beyond this threshold, rising population density is not associated with further increases in land intensification. Some measures of intensification actually show an alarming decline beyond this population density threshold. We also find a relatively weak relationship between population density and off-farm income. Overall, total household income per adult equivalent is found to decline significantly as population density rises. These findings raise serious policy questions about feasible pathways for rural poverty reduction in the context of increasingly land-constrained farming systems.

Background

Reducing poverty and hunger have been overriding policy concerns for the past half century in sub-Saharan Africa. More than 70% of the poor live in rural areas and derive more than half of their livelihood from farming. Broad based agricultural growth has been widely understood to be the most powerful vehicle for reducing rural poverty and kick-starting broader structural transformation processes (Johnston and Kilby, 1975; Mellor, 1995). A major feature of the structural transformation processes achieved in green revolution Asia was that it was *small farm-led* and *broad-based* (Johnston and Kilby, 1975; Mellor, 1995). Smallholders tend to spend their incomes on locally produced goods and services, therefore stimulating the domestic non-farm economy and creating additional jobs that would support diversification out of agriculture and demographic transition (Hazell et al., 2010; Bryceson and Jamal, 1997). For these reasons, a smallholder-led growth strategy has been touted as having the brightest prospects for rapid and sustained reductions in poverty and hunger in sub-Saharan Africa (Lipton, 2005; World Bank, 2007; Hazell et al., 2007; Byerlee and de Janvry, 2009; Haggblade, 2009; Christiaensen et al., 2011; Eastwood et al., 2010; Headey et al., 2010; Wiggins et al., 2010).

However, the widely held view that agricultural development and structural transformation in sub-Saharan Africa can be achieved by largely replicating the smallholder-led growth processes in Asia have seldom adequately taken account of the salient differences in farm structure and land productivity between Asia and Africa. Evidence from most African countries shows limited land productivity growth in response to rising population density (Headey and Jayne, 2014). Unlike in Asia, where land productivity growth was achieved with the aid of extensive irrigation/water control and improved seed varieties, which made high application rates of fertilizer use very profitable, by contrast most of Africa relies on rain-fed production. Moreover, especially in densely populated areas, soils have been continuously cultivated and are facing fertility constraints that make them less responsive to inorganic fertilizer (Drechsel et al., 2001; Marenya and Barrett, 2009; Tittonell and Giller, 2012; Sheahan et al., 2013). For these reasons, the economics of fertilizer intensification are quite different in much of Africa compared to green revolution Asia. Agricultural growth in sub-Saharan Africa (SSA) has historically been based on area expansion, not yield growth (Evenson and Gollin, 2003; Charles et al., 2010). However, continued area expansion is increasingly problematic, because of increased recognition of global environ-

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mental damage caused by the conversion of grassland and forests to agriculture (Powlson et al., 2011), because land expansion in some parts of rural Africa is not economic given current states of infrastructure, prices and production technology (Chamberlin et al., 2014), and in some areas because there is little or no unallocated land for further expansion.

Unavailability of land for cropland expansion is particularly serious in countries with high rural population densities such as Kenya. In 2010, 40% of Kenya's rural people resided on 5% of its rural land. Mean population density in these areas is 411 persons/km^2 of arable land. Population per arable kilometer of land in the Tegemeo Institute's nationwide rural household sample in 2010 was 412 and 598 persons per arable km^2 at the 50th and 75th percentiles of the distribution. Farm sizes are small and shrinking gradually as households subdivide their land to the next generation. Outmigration to towns and to more sparsely populated rural areas with arable land might be a possibility but there are well-known constraints to migration by members of one ethnic group to lands traditionally held by other ethnic groups (Kanyinga, 2009; Jenkins, 2012). We are increasingly concerned that development policy in the region has not adequately addressed how a smallholder-led agricultural strategy must be adapted to address the limitations of small and declining farm sizes and the growing problems of land accessibility in the densely populated areas that remain dependent on rain-fed production systems.

The overarching question addressed in this paper is whether and how farming systems are intensifying in response to rising rural population density in many areas of Africa. Kenya provides a good case study to examine these issues because a large proportion of the rural population resides in densely populated areas experiencing population pressures. Our study relies on five waves of panel survey data on 1,146 farm households interviewed between 1997 and 2010. This geo-referenced survey data is merged with geographic information systems (GIS) data on soil quality, arable land availability, and more disaggregated data on current and historical population numbers at the villages where the panel households are located.

There are particular situations where population growth has been associated with agricultural intensification and improved soil fertility. For example, Tiffen et al. (1994) presents a case study of agricultural intensification in the semi-arid district of Machakos, Kenya, where agricultural intensification occurred alongside a five-fold increase in population density over several decades up to 1990.[1] However, the association between population density and agricultural intensity does not necessarily infer causality. There could be feedback effects reflecting underlying endogeneity. For example, in Papua New Guinea, Brookfield (1972) encountered intensive practices in situations where there was no population pressure and extensive practices in areas where land was in great demand. To address these potential endogeneity issues, we develop a structural model for estimating the total impact of population density on smallholder households' behavior and various measures of agricultural intensification such as farm input use and farm output per unit of land and labor. The study provides an explicit modeling framework for determining the factors explaining farm productivity growth (or lack thereof) within the context of potentially endogenous population density changes. Most of the earlier studies examining the impact of population density on agricultural production in the region treated population density as exogenous (Benin, 2006; Pender and Gebremedhin, 2006; Pender et al., 2006). Our analysis may therefore avoid sources of coefficient bias and provide more accurate policy insights regarding a smallholder-led development strategy for densely populated areas.

Conceptual framework

Smallholder agriculture systems in sub-Saharan Africa are characterized by semi-commercial farms that produce multiple crops. These systems combine two fundamental units of microeconomic analysis, the household and the firm, that are highly interdependent. As opposed to the purely subsistence systems, in semi-commercial systems some farm inputs are purchased and some outputs are sold in the markets. To analyze the semi-commercial systems, we start with the theoretical framework proposed by Singh et al. (1986), popularly known as the *agricultural household model*. The framework captures the farm household's consumption and production interdependences in a theoretically coherent manner. In this framework, the objective of farm households is assumed to be maximization of expected household utility subject to budget and other resource constraints. Agricultural production either contributes to household's resource constraint through consumption or through cash generation if farm output is sold at market. Thus, agricultural production is incorporated as part of the household's budget constraints. Later, de Janvry et al. (1991) extended the original Singh et al. (1986) agricultural household model to include market failures while Omamo (1998) incorporated transactions costs. In the extended agricultural household model, the household problem is to maximize its utility:

$$\max U = U(X_a, X_m, X_l) \quad (1)$$

where the commodities are agricultural goods (X_a), market-purchased goods (X_m), and leisure (X_l). Utility is maximized subject to several constraints, among them: a cash constraint, production technologies for own-farming and nonfarm self-employment activities; exogenous effective prices for tradables; an equilibrium condition for self-sufficiency of farm production; and an equilibrium condition for family labor. First-order conditions of this model give a system of factor supply and demand functions, which in turn allows the estimation of factor inputs and supply functions.

At the minimum, the theory posits that the desired supply is a function of the expected output price, and supply shift variables such a vector of input prices, and the expected output and input prices of other production possibilities. Since the objective of this study is to examine how human population density affects smallholder agricultural production, the immediate task is to conceptualize how population density enters the input demand and output supply functions. A diagrammatic presentation of the channels through which population density influences smallholder production inputs and outcomes is presented in Appendix A. Assuming markets are allowed to operate freely and the appropriate price signals are transmitted to producers, escalating population density is hypothesized to affect agricultural production through three pathways, namely, decreasing land holding sizes, increasing labor supply, and increasing demand for food. Regarding the first two pathways, declining farm sizes are hypothesized to trigger changes in relative factor prices, consequently triggering changes in the land–labor ratio. The price of the scarce factor (land) is bid higher while the relative price of the more abundant factor (labor) declines. Regarding the third pathway, population growth directly affects the demand for agricultural products and exerts upward pressure on food prices thereby inducing a supply response. Other factors held constant, increasing demand for food triggers increased demand for non-mobile factor inputs thereby exerting putting more pressure on their prices as well.

According to the "induced innovation" theory, a change in the relative price of factors influence the factor use proportions (Hicks,

[1] Critics argue, however, that Machakos' land intensification was facilitated by exogenous factors unrelated to population density (e.g. Zaal and Oostendorp, 2000).

1932). A change in the relative prices of factors of production spur innovations aimed at economizing the use of a factor which has become relatively expensive. Since changes in population density influence input demand and output supply indirectly through prices, this process suggests a first-stage reduced form regression of output prices on population density variable among other relevant covariates. However, in a world characterized by market imperfections and transaction costs, factor prices may not fully pick up the effects of the increasing population pressure. For example, in many African countries, including Kenya, land sales markets are characterized by information asymmetry, enormous transaction costs, government bureaucracy, and ethnicity and cultural constraints. In such a case, increasing population density may affect landholding sizes and input demand and supply functions in ways that are not fully reflected in market prices. Thus, the existence of inefficient markets suggests a first stage reduced form regression of household landholding on population density among other relevant covariates as well as the inclusion of population density variable in the estimation of input demand and output supply functions.

While it is hypothesized that population density affects agricultural intensification, reverse causality is a distinct possibility. Population density drives food production (Boserup, 1965), while food production could also drive population density (Malthus, 1798). Besides, current indicators of land intensification potential and farm size may influence migration which will in turn affect future population density. Households in areas with low potential and/or declining land access may choose to migrate to areas which they perceive to be of relatively higher potential and/or better land access. To deal with potential population endogeneity, it is important to understand the exogenous drivers of population density. This will be helpful in identifying plausible population density instruments to be used later in the econometric modeling.

Economics as a discipline has paid little attention to population growth. The earliest conceptualizations of the drivers of population growth come from demographers and sociologists. Most of these studies have used *demographic transitions theory* to explain the causes and mechanisms behind human population changes over time (Notestein, 1945). According to the demographic transitions theory, as living standards rise and health conditions improve, first mortality rates decline and then, somewhat later, fertility rates decline (Kirk, 1996). People would naturally deploy the advantages of modernity to reduce death rates, but that fertility rates would be stalled by cultural factors that would only slowly give way (Notestein, 1945). Population growth is fuelled by two components: the "demographic momentum", which is built into the age composition of current populations, and changes in reproductive behavior, mortality and migration. As Fischer and Heilig (1997) explain, the 'echo effect' of a high-fertility period in the past creates a demographic momentum that counters reproductive control measures that favor smaller families. Perhaps this demographic momentum started when land was not a binding constraint and when most communities were not engaged in sedentary farming. During this time, it is assumed that human population densities were a function of diseases incidences and relatively uncorrelated with indicators of agricultural productivity (McMillan et al., 2011). No significant changes in fertility are expected to counter the demographic momentum since most developing countries have large rural populations whose fertility is driven by deep-rooted cultural norms and values, and religious beliefs. Other determinants of fertility include age at marriage (or beginning of sexual activity), prevalence and effectiveness of contraception, prevalence of induced abortion, and duration of postpartum infecundability, especially due to breast feeding (Lutz and Qiang, 2002). Speakers of the same language are generally expected to experience fertility transition at the same time (Johnson-Hanks, 2008).

Changes in reproductive behavior include changes in nuptiality and declines in marital fertility as suggested by Boserup (1965) and Malthus (1798). Changes in mother's literacy and infant mortality rates greatly influence fertility rates. Studies have found an inverse relationship between mothers' education attainment and family sizes (Fischer and Heilig, 1997). However, better health status of women increases fertility rates. The decline in mortality among infants resulting from the spread of modern hygiene and medicine is associated with decreased fertility. Adult mortality declines due to increased life expectancy as a result of diseases eradication or control with the advancement in modern medical technology.

As Bilsborrow (2001) explains, resource scarcity or depletion also drives human migration, which in turn affects population density. Migration, be it rural–urban or rural–rural, reduces population density in one area while raising it in others, as rural populations leave areas with scarce resources in search of resources and opportunities elsewhere. Perhaps the leading determinants of migration and displacement of people is caused by scarcity of water and land, conflicts over natural resources, natural hazards and natural disasters (Naude, 2010). Rural to urban migration could be caused by educational levels, and differences in wage rates and living conditions. Cultural factors such as psychological or emotional attachments to family, friends, and community may impede out-migration, while cultural similarities may facilitate in-migration; for example by non-locals who share a language, religion or ethnic affiliation. Government policies such as land tenure systems have been found to exert heterogeneous impacts on migration depending on how they are designed and implemented (Holden et al., 2009; Holden and Otsuka, 2014).

Data sources

The study draws from various data sources. First, is the nationwide Egerton University/Tegemeo Institute Rural Household Survey, a panel dataset tracking roughly 1300 small-scale farm households in 5 survey waves over the 13-year period from 1997 to 2010. The sampling frame for the panel was prepared in consultation with the Kenya National Bureau of Statistics (KNBS) in 1997. Twenty four (24) districts were purposively chosen to represent the broad range of agro-ecological zones (AEZs) and agricultural production systems in Kenya. Next, all non-urban divisions in the selected districts were assigned to one or more AEZs. Third, proportional to population across AEZs, divisions were selected from each AEZ. Fourth, within each division, villages and households in that order were randomly selected. In the initial 1997 survey, a total of 1500 households were surveyed in 109 villages spread across all major agroecological zones in the country. Subsequent surveys were conducted in June of 2000, 2004, 2007 and 2010. Over these 5 panel surveys, 1243 household were able to be consistently located and surveyed. For this analysis, households in the coastal region of the country were excluded because farming is found to account for a relatively small share of household incomes. This leaves a balanced panel of 1146 households surveyed consistently in each of the 5 years. The surveys collect information on demographic changes, movements of family members in and out of the household since the prior survey, landholding size, land transactions and renting, farming practices, the production and marketing of farm products, and off-farm income-earning activities.[2]

[2] Each of these survey instruments, which detail the types of information collected and used in this study, can be viewed and downloaded at http://www.aec.msu.edu/fs2/kenya/index.htm.

Attrition bias and life cycle effects are potential problems in panel data estimations. The average attrition rate between any two consecutive rounds is about five per cent. While longitudinal survey data may be random and representative in the initial survey wave, successive waves may be less representative because of attrition. Re-interview models similar to those estimated in Jin and Jayne (2013) indicate that observed attrition is largely random, and hence selection bias caused by attrition is not likely to be a problem.[3]

In a 13-year panel such as this one whereby the age distribution of the sample increases over time, variables such as households' landholding size and cultivated land are likely to be subject to life cycle effects. To control for life cycle effects when examining bivariate changes over time in variables correlated with age of the household head (e.g. landholding size), we regressed landholding size on household demographic variables (e.g. age, gender, and the level of education of the household head) using OLS using data from the initial year survey, which is considered representative of the age distribution of the rural population unlike subsequent waves of the panel which are affected by life-cycle effects. The coefficient on the household heads' age variable was used to adjust for the life cycle effects on landholding size, cultivated area, and family size in the bivariate tables only.

The household panel survey instrument captured the geographic positioning system (GPS) coordinates of each household. This made it possible to compliment the survey data with geographic information systems (GIS)[4] data on soil quality and more disaggregated data on current and historical population numbers at the villages where the panel households are located. Data on population densities was extracted from the Global Rural–Urban Mapping Project (GRUMP)[5] and AfriPop[6] Project. For each 10×10 km pixel, the population estimates were divided by arable land area (land currently cultivated plus grassland and forest land that is potentially cultivable). The arable land data came from the GlobCover2009 project.[7] It is important to mention that the urban component of population as well as urban grid cells was netted out. Thus, the population estimate is the average rural population count per pixel for each rural pixel.

The historical population density used to explain population density growth momentum came from the History Database of the Global Environment (HYDE)[8] dataset. The database is a collection of gridded time series of population and land use going back 12,000 years in 10-year time steps. The methods used in this ''hindcasting'' are detailed in Goldewijk et al. (2011). Data on the proportion of women who can read and write, fertility (age of women at first marriage, proportion of women using contraceptive, and age of women at first intercourse) and mortality (number of children who have died per woman) indicators came from MEASURE Demographic and Health Surveys (DHS).[9] However, this data was only available at the division level.

The other variable extracted from the GIS sources was the length of the growing period (LGP, Fischer et al., 2000), which combines information on temperature and available moisture to determine the length of time for adequate crop growth. Elevation and slope variables were extracted from Shuttle Radar Topography Mission (SRTM)[10] data.

The study also used monthly wholesale price data for maize and for each of the main food and cash crops collected from regional wholesale markets across Kenya by the Market Research and Information Department of the Ministry of Agriculture. Data on rainfall came from the Climate Prediction Center and are part of the USAID/Famine Early Warning System (FEWS) project. This data interpolates rainfall estimates based on data from rain stations as well as satellite data (such as on cloud cover and cloud top temperatures). The FEWS rainfall estimates were then matched to Tegemeo panel survey households using their GPS coordinates. From the rainfall data, expected rainfall and expected drought shock variables were generated.[11] Expected rainfall is defined as a 6-year moving average of rainfall prior to the main growing season in survey year, while expected drought shock is a 6-year moving average of the percentage of 20-day periods during the main growing season with less than 40 mm of rainfall.

Analytical methods

We first use bivariate descriptive analysis to examine how various groupings of the sample stratified by village-level population density evolve over the panel period in terms of demographic trends, farming patterns and farm production. The mean population densities in the sampled districts ranged from 44 persons/km^2 in the case of Laikipia West to 965 persons/km^2 in Vihiga District. We then sort these 109 villages by population density and next stratified them into five equal population density groups, or quintiles. Population densities range from 30 to 147 persons/km^2 in the lowest quintile, 148–313 in the second quintile, 315–470 in the third quintile, 475–655 in the fourth quintile, and 659–1135 persons/km^2 in the highest quintile. We then examine how the five categories of farms are evolving differently over the 1997–2010 period in terms of their farming systems (e.g. changes in farm size, land rental rates, cropping patterns and factors intensities) and measures of household asset wealth and incomes from crops, animal production, and non-farm sources.

Turning to our econometric model, we are interested in measuring the *ceteris paribus* effect of land scarcity, proxied by population density per hectare of arable land, on smallholder input demand and output supply. There are two salient econometric identification challenges. First, population density is potentially endogenous in the factor demand and output supply models. Second, and as mentioned in the conceptual framework, population density may influence input demand and output supply through its effects on farm size, input factor prices and output prices, or potentially in other ways that are not explicitly modeled.

To address the endogeneity challenge, we used the control function (CF) approach (Wooldridge, 2010), which provides a straightforward endogeneity test for the potentially endogenous variable. To implement the CF method in this case we require the availability of at least one instrumental variable (IV); a variable that is correlated with population density but uncorrelated with indicators of land intensification.

We address the problem of indirect and direct potential effects of population density by adopting the following estimation strategy: (i) first stage estimation of population density on a vector of covariates where at least one of them is a plausible instrumental variable; (ii) second stage estimation of a maize price model whereby population density enters as a covariate while controlling for its potential endogeneity; and (iii) third stage estimation of input factor and output supply functions where population density and its residuals from the first stage regression, the expected maize price (predicted maize values from the second stage regression)

[3] Results are not shown here to conserve space, but are available upon request.

[4] We thank Jordan Chamberlin for extracting the GIS data used in this study.

[5] See http://sedac.ciesin.columbia.edu/gpw/docs/UR_paper_webdraft1.pdf.

[6] See http://www.afripop.org/.

[7] See http://due.esrin.esa.int/globcover/.

[8] HYDE data is available here http://themasites.pbl.nl/en/themasites/hyde/index.html.

[9] Available here http://www.measuredhs.com/data/data-collection.cfm.

[10] Available here http://srtm.csi.cgiar.org/.

[11] These variables were computed by David Mather.

and input factor prices enters the vector of the covariates. Consequently, we estimate the following models:

First stage: Population density equation

$$D_{it} = H_i\kappa + \varepsilon_i \quad (2)$$

Second stage: Maize price equation

$$P_{it} = \rho_{01}D_{it} + U_{it}\eta_0 + \theta_0\hat{\varepsilon}_{it} + c_{0,i} + \mu_{0,it} \quad (3)$$

Third stage: Input factor prices, farm size, input demand and output supply equations

$$F_{it} = \rho_{11}D_{it} + \gamma_{11}\hat{P}_{it} + W_{1,it}\eta_1 + \theta_1\hat{\varepsilon}_{it} + c_{1,i} + \mu_{1,it} \quad (4)$$

$$L_{it} = \rho_{21}D_{it} + \gamma_{21}\hat{P}_{it} + W_{2,it}\eta_2 + \theta_2\hat{\varepsilon}_{it} + c_{2,i} + \mu_{2,it} \quad (5)$$

$$X_{it} = \rho_{31}D_{it} + \gamma_{31}\hat{P}_{it} + Z_{it}\eta_3 + F_{it}(D_{it})\lambda_3 + \tau_3L_{it}(D_{it}) + \theta_3\hat{\varepsilon}_{it} + c_{3,i} + \mu_{3,it} \quad (6)$$

$$Q_{it} = \rho_{41}D_{it} + \gamma_{41}\hat{P}_{it} + Z_{it}\eta_4 + F_{it}(D_{it})\lambda_4 + \tau_4L_{it}(D_{it}) + \theta_4\hat{\varepsilon}_{it} + c_{4,i} + \mu_{4,it} \quad (7)$$

In the first stage, we estimate the population density Eq. (2). The dependent variable, D_{it}, is measured at the village level and is defined as the number of persons per square kilometer of the potentially arable land rather than the standard total surface area; H_{it} is a vector of covariates including unity as its first element and other variables that influence population growth as identified in the conceptual framework section, including land quality indicators (length of growing period, elevation and slope), village population size in 1950 (to capture the 'echo effect' of past population density), women literacy indicators, distances to water source, religious affiliation, contraceptive use, age at first marriage and first intercourse, child mortality, and ethnicity. Most of these covariates are hypothesized to be correlated with population growth variable but uncorrelated with agroecological potential where these households are located, thus being plausible instrumental variables. While the population density model is required to implement the control function approach, a population density model is also useful in its own right to identify the factors responsible for spatial variations in localized population growth.

In the second stage, the maize price model (3) equation is estimated. The dependent variable price vector P_{it} is the price of maize per kilogram. The vector U includes one as its first element, household ownership of means of transport (truck and/or bicycle), distances from the homestead to the nearest infrastructural faculties, level of investment in storage facilities, maize buyer type, regional maize price at planting time, National Cereals and Produce Board (NCPB) maize prices in the previous year, and demographic characteristics of the household head (gender, age, and level of education). In the second and third stage models, we include the population density variable and its squared term based on the bivariate non-parametric regression results, to test for any remaining effects that density might have on behavior that is not explicitly modeled in Eqs. (3)–(6). We refer to the potential effects of population density in Eq(7) as "direct" effects, although any such effects signify inability to fully model the complex structural pathways by which density may affect the outcome variables in (7). Our null hypothesis is that $\hat{\rho} = 0$, that is, that there are no direct effects of population density after accounting for its effects in Eqs. (3)–(6). The residuals ($\hat{\varepsilon}_{it}$) from the first stage population density estimation (Eq. (1)) are also included in Eq. (7). The inclusion of the residuals ($\hat{\varepsilon}_{it}$) from the first stage population density regression into the second stage regressions breaks the endogeneity link between the population density variable and the error terms (μ) in the second and third stage models (i.e. this is the Control Function implementation). The null hypothesis $\hat{\theta} = 0$ tests the exogeneity of population density variables in the second and third stage models. While c represents the unobserved time-constant effects, μ represents the unobserved time-varying effects.

The third stage entails estimation of models 4 through 7. The dependent variable price vector F_{it} includes land rental rates per hectare for a year, and agricultural wage rate per day. Unfortunately, data on land sales prices are limited. Moreover, land sales markets are characterized by high transaction costs and thus assumed to be inefficient. Consequently, we model household landholding size (L_{it}) directly. We also do not model fertilizer prices since fertilizer prices are not determined locally but are generally regarded as being determined by international markets and transport costs. The dependent variable X_{it} represents the intensity of fertilizer and purchased input use per hectare owned while the dependent variable Q_{it} represents crop production per hectare owned.

Smallholder production systems in sub-Saharan Africa are highly diversified and are partially integrated into the markets. This situation presents a challenge for modeling in a number of ways. First, farmers grow a wide array of crops on one land plot each season and crop enterprises vary across agroecological zones making it difficult to obtain a balanced panel data on crop production and the respective prices. Second, the wide array of crops produced implies too few degrees of freedom for statistical modeling. Given these circumstances, it becomes imperative to aggregate the outputs in some manner. To aggregate crop production across multiple commodities, we convert crop production into monetary values using prices and the modification of the Fisher-Ideal index suggested by Mason (2011).

Next we discuss the explanatory variables used in the third stage models. Just as in the estimation of model (3), the population density variable and its residuals ($\hat{\varepsilon}_{it}$) from the first stage regression are also included. We also include the predicted maize prices ($\hat{P}$) from the second stage maize model estimation as a proxy for the farmers' output price expectations. It is important to note that vectors W and Z include unity as the first element. The vector W_1 in model (4) include the district mean land holding sizes, land quality variables, distances to infrastructural faculties, naïve expectation of maize and beans prices—prices prevailing in the regional markets at the planting time, survey year and agricultural zone dummies. The vector W_2 in model (5) include household demographic variables, (gender, age, education attainment of household head and household size), land holding of the household of the household head's father before sub-division, land holding of the spouse's father before sub-division, household duration in the current location, and tribe and survey year dummies. The vector Z in models (6) and (7) includes land productivity variables (length of growing period, net primary productivity, elevation and slope); expected rainfall and expected drought shocks; fertilizer price; distance to the nearest motorable road; ownership of radio (access to information); and household demographic variables (gender, age, and level of education of the household head and household size).

The third stage models are estimated as a system using the correlated random effects (CRE) approach (Mundlak, 1978; Chamberlain, 1984). We use CRE because some of the covariates in these models are time constant and thus drop out if fixed effects (FE) estimation approach is used.[12] The CRE approach involves the inclusion of the long-term average of each time-varying variable in

[12] Random effects (RE) also allow the inclusion of time-constant variables. However, the assumption that fixed effect factor is not correlated with the explanatory variables is often not plausible.

the model in order to control for unobserved time-invariant heterogeneity under the assumption that the time-averages are correlated with the unobserved time-invariant heterogeneity (Wooldridge, 2010). Provided that this assumption holds, estimation results from CRE are equivalent to those of FE for the time-varying elements of the model.

To compute the total partial effects of the population density on input demand and output supply function we use the following method:

$$\frac{\partial X_{it}}{\partial D_{it}} = \underbrace{\frac{\partial X_{it}}{\partial D_{it}}}_{DIRECT} + \underbrace{\left[\left(\frac{\partial X_{it}}{\partial F_{it}} \times \frac{dF_{it}}{dD_{it}}\right) + \left(\frac{\partial X_{it}}{\partial L_{it}} \times \frac{dL_{it}}{dD_{it}}\right)\right]}_{INDIRECT} \quad \text{Input demand} \tag{8}$$

$$\frac{\partial Q_{it}}{\partial D_{it}} = \underbrace{\frac{\partial Q_{it}}{\partial D_{it}}}_{DIRECT} + \underbrace{\left[\left(\frac{\partial Q_{it}}{\partial F_{it}} \times \frac{dF_{it}}{dD_{it}}\right) + \left(\frac{\partial Q_{it}}{\partial L_{it}} \times \frac{dL_{it}}{dD_{it}}\right)\right]}_{INDIRECT} \quad \text{Output supply} \tag{9}$$

It is also important to mention that since the estimation of the second and third stage models involve generated regressors, standard errors generated by most econometric software for the coefficients are not valid since they ignore the sampling variation in the estimation of the coefficients in the first two steps. Disregarding the sampling error in the generated regressors is likely to underestimate the computed standard errors. Consequently, each of the models in the third stage are estimated separately but within the same bootstrap as the first and second stage models with 500 replications to get a valid estimate of the standard errors. Inferences are also made fully robust to arbitrary heteroskedasticity and serial correlation. The results from the input demand and output supply models are presented in the next section. The summary statistics of the variables used in the estimations are presented in Appendix B.

Results and discussion

Descriptive results

This section discusses bivariate relationships between population density, landholding size and the various outcomes of interest as a prelude to the econometric findings. Due to space limitations, only results based on the GRUMP population density are presented but in all cases they are highly consistent with findings based on the use of AfriPop population density estimates. Table 1 presents information on farm size and farming practices by village population density quintiles over the four survey years. The results clearly show that landholding sizes and areas under cultivation are inversely related to population density and have been declining over time. Landholdings among smallholders in the most densely populated 20% of villages are a quarter the size of those in the 20% least densely populated villages. Over the 10-year panel period, mean landholding sizes in the former and latter groups were 0.96 ha and 3.78 ha, respectively. Areas under cultivation have also declined somewhat over the 10-year panel period for most of the population density categories. Area under cultivation in the highest density quintile averaged 0.90 ha per farm, about half that in the lowest density quintile. The proportion of farmland under fallow (landholding less area not under crop) has also declined by about 20% over time across all the population density quintiles. The percentage of farmland under fallow is inversely related to population density, ranging from a high of 50% in the most sparsely populated quintile of villages to a low of 6% in the most densely populated group of villages.

Next, we examine how the prices and quantities of major agricultural inputs vary across population density quintiles. Family labor, defined as the number of adult equivalents (adjusted to the number of months spent in the household), per hectares of land cultivated, has generally increased over the 13-year period, and is highest in the 20% densely populated villages (Table 1). Similarly, the 2010 land values were more than twice as high in the three highest population density quintiles than in the lowest density quintile. Information on land values was only collected in the 2010 survey. Results also show that agricultural wage rates in the lowest densely populated villages are 30% higher than in the highest densely populated areas (Table 1). Capital expenditure, defined as the cost of purchased inputs (cost of fertilizer, seed and land preparation) per hectare seems to be an increasing but non-linear function of population density. It increases with population density from the first (lowest) quintile up to the fourth but declines in the fifth (highest) quintile.

The relationships between inputs use and population density are further clarified when examining the non-parametric regression results presented in Figs. 1 and 2. In all the graphs (Figs. 1–8), the *x*-axis shows population density (persons/km^2) while the *y*-axis shows the variable of interest. The *x*-axis also shows the population density levels corresponding to various percentiles of the distribution: 25 percentile (204 persons/km^2); 50 percentile (412 persons/km^2); 75 percentile (598 persons/km^2); and 90 percentile (874 persons/km^2). The solid curve shows the bivariate relationship between the variable of interest and population density while the dotted curve presents the post-estimation simulation of the relationships between the same variables when other variables are controlled for. Fig. 1 shows the non-parametric regressions of fertilizer use per hectare cultivated on population density. The fertilizer use intensity increases with population density up to about 600 persons/km^2 and declines thereafter. Similarly, the intensity of purchased inputs (fertilizer, seed and chemicals, hired land preparation costs) use is also an increasing but non-linear function of population density (Fig. 2). Just as observed in Table 1, household's cultivated land declines with population density (Fig. 3).

Table 1 also presents trends in farm production and household income over the panel period by village population density quintiles. The value of net crop and farm income (gross income minus input costs) per hectare and farm income per unit of labor, a measure of partial land productivity, increases with population density up to the fourth density quintile and declines thereafter. This finding is consistent with the non-parametric regressions showing that the crop intensification are increasing functions of the population density up to a certain threshold, about 600 persons/km^2, and declines thereafter (Fig. 4). The value of net farm income (from crops and animal products) per hectare owned or per unit of labor shows a similar non-linear relationship with population density (Figs. 5 and 6). Similarly, total household incomes rise with population density up to the fourth population density quintile, and thereafter starts to decline (Table 1). The non-parametric regression results too show the same picture of household aggregate income increasing with population density up to about 400 persons/km^2 and falling thereafter (Fig. 7). While the bivariate analysis does not show a clear relationship between household off-farm income and population density (Table 1), the non-parametric regressions show that households' off-farm incomes rise with population density up to about 400 persons/km^2 and decline thereafter.

Next, we discuss the value of asset wealth per adult equivalent by population density quintiles (Table 1). The list of productive assets consistently collected and valued in each of the four surveys includes ploughs, tractors and draft animal equipment, carts, trailers, cars, trucks, spray pumps, irrigation equipment, water tanks, stores, wheelbarrows, combine harvesters, cows, bulls, donkeys,

Table 1
Farming practices, factor intensities and household income, by pop. density quintile.

Nominal terms	Pop. density quintile[a]	Survey year				Four survey panel	
		2000	2004	2007	2010	Average	95% CI
Landholding[b] (ha)	5 [highest]	1.28	0.95	0.88	0.76	0.96	[0.78 1.15]
	4	1.63	1.36	1.17	1.05	1.33	[1.23 1.44]
	3	2.06	1.57	1.19	1.17	1.55	[1.38 1.71]
	2	2.90	2.66	2.38	2.05	2.52	[2.26 2.79]
	1 [lowest]	3.89	3.80	3.79	3.37	3.78	[3.48 4.08]
Area cultivated in the main season (ha)	5 [highest]	1.02	0.92	0.87	0.74	0.90	[0.82 0.99]
	4	1.24	1.17	1.12	0.98	1.15	[1.08 1.22]
	3	1.49	1.45	1.03	0.94	1.26	[1.16 1.36]
	2	2.14	1.82	1.70	1.37	1.69	[1.58 1.81]
	1 [lowest]	2.79	1.94	1.90	1.80	1.93	[1.79 2.07]
Labor[b] per hectare cultivated	5 [highest]	3.49	3.66	3.93	4.16	3.72	[3.67 3.76]
	4	2.77	2.78	2.87	3.31	2.85	[2.81 2.89]
	3	2.50	2.24	3.03	3.13	2.58	[2.52 2.63]
	2	1.70	1.94	2.01	2.32	2.03	[1.97 2.10]
	1 [lowest]	1.26	1.65	1.75	1.71	1.70	[1.62 1.77]
Cost of purchased inputs per hectare ('000 KSh)	5 [highest]	12.53	12.85	11.32	13.25	12.49	[11.70 13.27]
	4	15.76	17.68	14.72	18.23	16.60	[15.41 17.80]
	3	11.19	13.09	10.67	14.57	12.38	[10.88 13.88]
	2	5.25	10.26	10.52	12.05	9.52	[8.45 10.58]
	1 [lowest]	7.45	7.25	7.47	9.01	7.80	[6.53 9.06]
Land value/hectare ('000 KSh)	5 [highest]	–	–	–	703.02	703.02	[541.27 864.78]
	4	–	–	–	633.03	633.03	[359.66 906.40]
	3	–	–	–	723.67	723.67	[479.64 967.70]
	2	–	–	–	626.00	626.00	[276.30 975.70]
	1 [lowest]	–	–	–	271.82	271.82	[103.76 439.87]
Hired agricultural wage labor rate (KSh/day)	5 [highest]	54.50	57.34	56.45	65.68	58.49	[57.70 59.27]
	4	65.50	77.74	74.07	88.24	76.39	[75.20 77.59]
	3	62.25	63.63	64.88	75.41	66.54	[65.04 68.04]
	2	63.83	76.97	74.49	85.98	75.31	[74.24 76.37]
	1 [lowest]	76.47	80.99	81.41	80.03	79.73	[78.46 80.99]
Net farm income per hectare owned '000 KSh	5 [highest]	74.20	69.57	46.15	47.75	56.88	[49.65 64.12]
	4	69.20	69.83	46.07	83.81	62.69	[57.63 67.74]
	3	40.70	45.28	36.33	53.24	41.25	[37.52 44.99]
	2	29.02	38.28	35.29	40.03	34.62	[30.92 38.31]
	1 [lowest]	29.26	29.61	16.41	10.21	22.12	[20.05 24.19]
Net farm income per unit of labor '000 KSh	5 [highest]	31.01	29.08	18.03	17.00	21.99	[18.75 25.23]
	4	36.31	32.80	22.92	41.72	30.40	[27.19 33.61]
	3	25.55	23.85	21.45	30.18	23.23	[20.69 25.77]
	2	24.02	27.73	28.75	34.06	28.02	[22.59 33.44]
	1 [lowest]	30.08	37.56	19.94	29.70	27.37	[14.52 20.23]
Off-farm income per adult equivalent '000 KSh	5 [highest]	8.45	11.11	10.75	13.24	10.28	[9.08 11.47]
	4	10.91	16.56	18.54	28.38	16.63	[13.73 19.54]
	3	8.59	11.85	13.20	15.74	11.21	[9.56 12.85]
	2	9.82	12.66	12.87	19.14	12.67	[10.73 14.61]
	1 [lowest]	12.50	13.17	15.95	17.80	13.46	[11.58 15.34]
Household aggregate annual income '000 KSh	5 [highest]	26.95	25.20	25.74	29.36	24.67	[22.56 26.74]
	4	31.83	38.33	40.09	64.27	38.72	[34.61 42.77]
	3	24.29	26.78	29.39	37.78	26.75	[24.17 29.25]
	2	22.45	28.27	30.86	42.98	29.39	[26.04 32.70]
	1 [lowest]	29.35	35.01	38.15	31.55	30.61	[27.19 34.07]
Value of assets/wealth per adult equivalent	5 [highest]	7.91	8.49	10.58	8.49	8.77	[7.64 9.89]
	4	11.06	12.93	21.01	20.47	15.32	[12.47 18.17]
	3	8.41	12.69	14.37	16.82	12.27	[10.61 13.92]
	2	13.11	15.82	15.09	20.83	16.80	[14.51 19.09]
	1 [lowest]	24.20	36.55	38.26	39.10	32.06	[27.68 36.43]

Source: Tegemeo Institute Rural Household Surveys.
[a] Population density quintiles are defined by ranking all households in the surveys by village-level population density and dividing them into five equal groups.
[b] Labor is defined as the number of adult members in the household accounting for time spent in non-resident status.

and smaller animals. Recent studies in the poverty literature (e.g. Carter and Barrett, 2006; Krishna et al., 2004) argue that the value of assets more accurately measures wealth than income or consumption, as it is less susceptible to random shocks, and is likely to be a more stable indicator of household welfare. This is especially true in regions where rain-fed agriculture is a major source of annual income and where households rely greatly on their physical assets for their livelihoods. For these reasons, we consider asset holdings to be an important measure of household productive potential and food security. The results show that asset wealth per adult equivalent has been consistently higher (by a factor of two) in households located in areas of relatively low population density (Table 1). Family size in adults and adult equivalents is almost the same across all five population density quintiles, meaning that asset wealth per household is also substantially higher on average in the low-density areas.

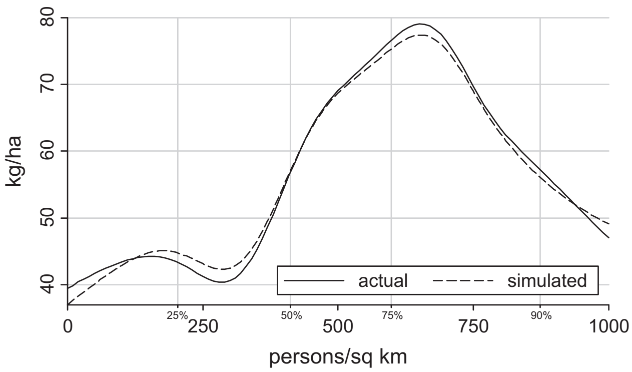


Fig. 1. Fertilizer quantities applied per hectare cultivated.

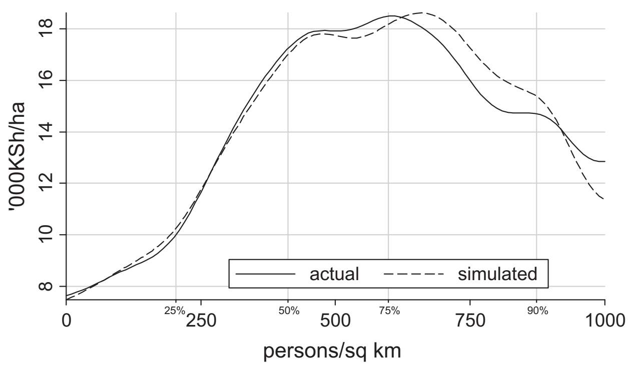


Fig. 2. Total value of cash input expenditures per ha cultivated.

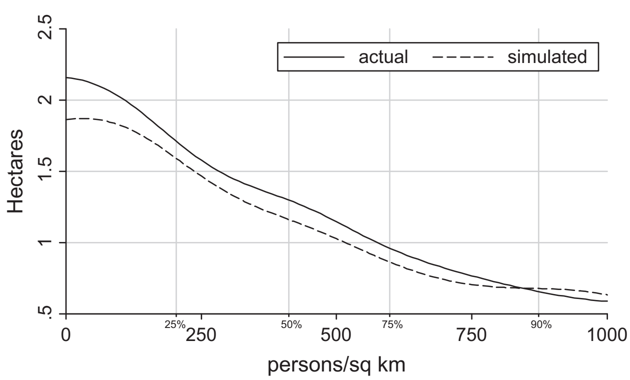


Fig. 3. Area cultivated per household.

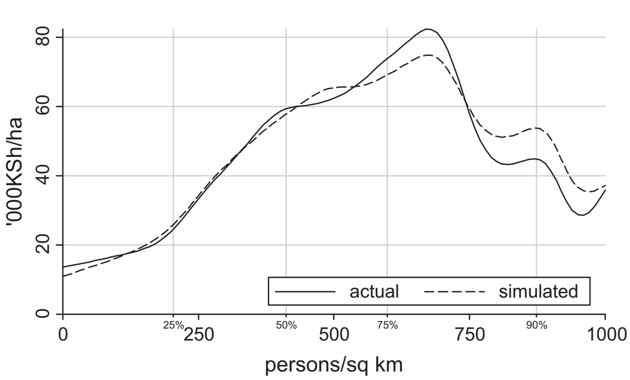


Fig. 4. Net crop income per hectare owned.

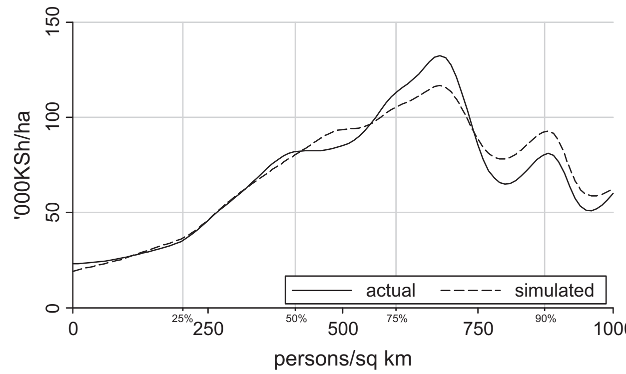


Fig. 5. Net farm income per hectare owned.

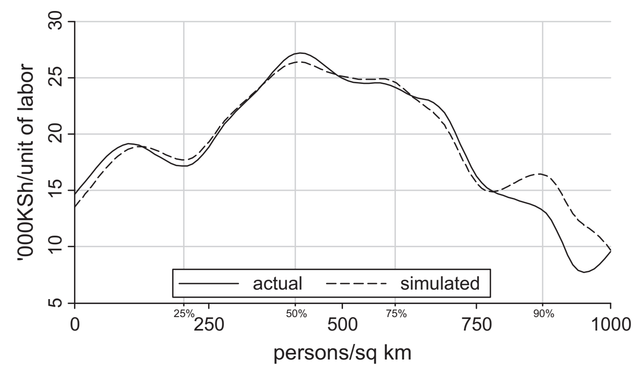


Fig. 6. Net farm income per unit of family labor (resident adults).

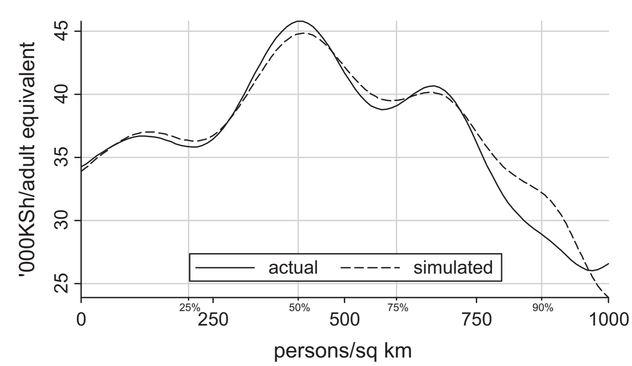


Fig. 7. Aggreage household income per adult equivalent.

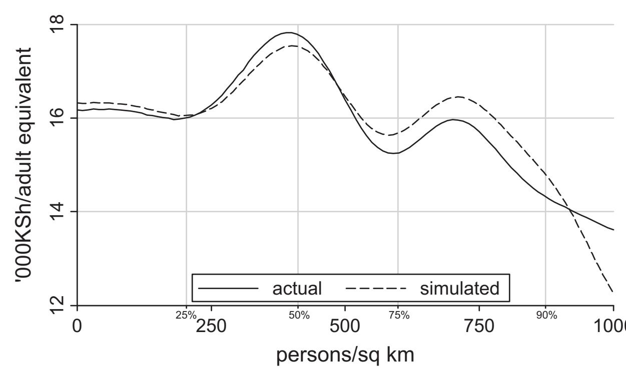


Fig. 8. Non-farm income per adult equivalent.

The overall picture emerging from these bivariate findings is smallholder agricultural practices are becoming more land-intensive as population density rises, and that indicators of agricultural productivity and rural livelihoods are declining as population density rises beyond a certain threshold. However, these bivariate relationships do not control for the effects of other variables affecting farm productivity, incomes and asset wealth, and so we now turn to more rigorous econometric analysis in the next section.

Econometric results

Given the suspected endogeneity of population density in models of input demand and output supply, we first discuss results from the reduced form estimations of population density (Eq. (2)), which are presented in Table 2. Most of the explanatory variables are statistically significant and bear the expected signs. Among the significant drivers of population density growth include women's literacy and fertility indicators (age at first birth, age at first marriage, age at first intercourse, and use of contraceptives), infant mortality indicators, and indicators of agricultural potential of the locations where the households are located.

As mentioned in the methods sections, residuals from the population density reduced form estimation are incorporated in the input and output prices, landholding, and input and output supply estimations to control for population density endogeneity. The population density variable was found to be endogenous in these models, as the residuals from the first stage models were almost always found to be statistically significant at the 0.05 level.

Effects of population density on maize price levels

Table 3 presents the second stage maize price model results from Eq. (3). The results show that maize prices are not directly influenced by population density. As we had hypothesized, population density does not have a significant effect on maize prices once other variables are controlled for due to trade effects. The other important correlates of maize price include type of maize buyers, the maize prices prevailing at the regional markets at the planting time, the National and Cereal Produce Board (NCPB) previous year's maize buying prices in the region, and the length of growing period.

Effects of population density on agricultural wages and land rental rates

The agricultural wage rate is found to be a decreasing function of population density over 99% of the distribution as we would expect (Table 4). The average partial effects (APEs) reported in Appendix C show that an increase in population density by 100 persons/km^2 reduces wage rates by about 20%. Also reported in Appendix C are the population partial effects on wage rate at various population density percentiles. The partial effects show that wage rate decreases with population density but at a declining rate. Other variables that influence positively agricultural wage rates are reduced distances to infrastructural facilities, expected maize prices, and the agricultural potential of the areas where the households are located. Also as expected, land rental rates are found to increase with population density over the relevant range of the data (Table 4). Land rental rates increase with population density but the rate of increase is more gradual at high levels of population density (Appendix C). Land rental rates reach a maximum at about 1138 persons/km^2. The APEs indicate that an increase in population density by 100 persons/km^2 increases land rental rates by about 2%. Other variables that significantly influence land rental rates include the expected maize price, district landholding sizes, and distance to electricity supply. Equilibrium rental rates are higher if leasers and leaseholders expect high crop prices; in this manner, maize price supports through Kenya's crop marketing board appear to be capitalized into land values. Weather conditions and agroecological potential as proxied by the length of growing period (LGP), slope and elevation also influence land rental rates.

Table 2
OLS estimation results for population density.

Dep. var.: log of population density (persons/km^2)	Coef.	$P > t$
Length of Growing Period (LGP)	0.003	0.00
Elevation: '00 m above sea level	0.181	0.00
Elevation squared	−0.003	0.00
Slope: measure of steepness – degrees	0.041	0.00
Estimated population count for 1950 ('00 persons)	0.015	0.00
Women literacy rate (proportion)**	−1.588	0.00
Mean distance to water source – km**	−0.002	0.00
Religion (proportion of Catholics)**	5.292	0.00
Women-average age at first birth**	−0.993	0.00
Contraceptive use (proportion)**	−2.360	0.00
Women: average age at first marriage**	−0.647	0.00
Women: average age at first intercourse**	−0.127	0.00
Average number of children dead per woman**	−1.447	0.00
_cons	13.777	0.00
Number of obs.	5845	
R squared	0.890	

Note: Ethnic community dummies included.
** Division-level variables from DHS survey (see data section).

Table 3
CRE estimation results for producer farm gate maize prices.

Dependent variable: log of maize price/kg (KSh)	Coef.	$P > z$
Population density (100 pp/sq km)	0.007	0.54
Distance to motorable road (km)	−0.003	0.27
Distance to tarmac road (km)	0.004	0.69
Own a truck (1 = yes; 0 = no)	0.039	0.14
Own a bicycle (1 = yes; 0 = no)	−0.004	0.65
Own a radio (1 = yes; 0 = no)	0.009	0.40
Storage facility – estimated value ('000 KSh)	0.002	0.41
Maize buyer type (base = private buyer)		
NCPB	0.091	0.00
Processor	0.139	0.00
Other	0.077	0.00
Regional maize price/kg – planting time	0.008	0.00
NCPB previous years buying price/kg	0.012	0.01
Sex of household head (1 = male; 0 = female)	−0.004	0.77
Age of the household head (years)	0.005	0.41
Education attainment (# of years)	0.001	0.49
Length of Growing Period (LGP)	0.001	0.00
Elevation: '000 m above sea level	0.010	0.61
Slope: measure of steepness – degrees	0.001	0.73
First stage population density residuals	−0.062	0.29
_cons	2.921	0.00
Observations	5845	
Number of households	1169	

Note: Time averages of time varying variables; and agroecological zones and survey year dummies included.

Effects of population density on farm sizes, cultivated area and land under fallow

Household landholding sizes and land under cultivation decrease with population pressure (Table 5). If population density increases by 100 persons/sq km^2, household landholding and area under crop decline by about 16% and 17%, respectively. Land under fallow also decline with population density. An increase in population density by 100 persons reduces fallow land by about 19%. Household landholding sizes and cultivated areas decrease with land rental rates. Considering these effects in relation to those in Tables 3 and 4 reveals that rising population density in rural Kenya has produced many complex effects. On the one hand, rising

Table 4
CRE estimation results for agricultural wage and land rental rates.

	Log of wage rate (KSh/day)		Log of land rental rates (KSh/ha)	
	Coef.	*P* > *z*	Coef.	*P* > *z*
Population density (100 pp/sq km)	−0.287	0.00	0.091	0.00
Population density square	0.013	0.00	−0.004	0.00
Distance to motorable road (km)	−0.009	0.01	−0.001	0.80
Distance to tarmac road (km)	−0.004	0.00	0.003	0.82
Distance to water source (km)	0.014	0.27	−0.004	0.51
Distance to health center (km)	−0.002	0.02	−0.003	0.84
Distance to electricity supply (km)	−0.004	0.05	−0.031	0.01
Length of Growing Period (LGP)	0.003	0.00	0.014	0.00
Elevation: meters above sea level	0.008	0.00	0.005	0.00
Slope: measure of steepness – degrees	0.012	0.00	−0.089	0.00
Expected maize price/kg	0.020	0.00	0.048	0.00
District median landholding (ha)	–	–	−0.030	0.02
First stage population density residuals	−0.044	0.00	−0.059	0.00
_cons	2.878	0.00	6.243	0.00
Observations	5845		5845	
Number of households	1169		1169	

Note: Time averages of time varying variables; agroecological zones and survey year dummies included.

Table 5
CRE estimation results for household landholding, land under cultivation and fallow.

	Log land owned (ha)		Log cultivated land (ha)		Log land under fallow (ha)	
	Coef.	*P* > *z*	Coef.	*P* > *z*	Coef.	*P* > *z*
Population density (100 pp/sq km)	−0.159	0.00	−0.169	0.00	−0.186	0.01
Household size	0.026	0.00	0.036	0.00	0.017	0.18
Sex of household head (1 = male; 0 = female)	0.045	0.20	0.048	0.19	0.081	0.30
Age of the household head (years)	0.006	0.00	0.005	0.00	0.002	0.94
Education attainment (# of years)	0.008	0.06	0.011	0.02	0.007	0.34
Land rental rates ('000 KSh)	−0.014	0.06	−0.025	0.02	0.015	0.38
Landholding – father of initial head (ha)	0.005	0.00	0.004	0.00	0.005	0.00
Landholding – father of the spouse (ha)	0.002	0.09	0.002	0.05	0.001	0.62
# of years in the current location	0.005	0.08	0.007	0.01	0.002	0.58
Length of Growing Period (LGP)	0.001	0.18	0.003	0.00	−0.001	0.55
Elevation ('000 m above sea level)	0.105	0.58	0.000	0.42	0.198	0.55
Slope (measure of steepness – degrees)	−0.004	0.84	−0.030	0.04	−0.009	0.78
First stage population density residuals	0.001	0.00	0.001	0.00	0.001	0.31
_cons	−1.098	0.00	−1.574	0.00	−0.771	0.13
Observations	5845		5845		5845	
Number of households	1169		1169		1169	

Note: Time averages of time varying variables, and agroecological zone dummies, ethnic tribe and survey dummies included.

population density is associated with smaller farms and more intensive use of available land. Rising population density also increases land rental rates, which exert further downward pressure on cultivated area. Besides population density, other variables such as land rental rates, household demographic characteristics, intergenerational factors, and ethnicity as captured by the household head's tribe also influence household landholding sizes. The more land controlled by the father to the household head, the more land on average is controlled by the current household.

Effects of population density on input factor demand

Results presented in Table 6 show that the use of fertilizer and other purchased inputs per hectare cultivated increase with population density up to about 617 and 729 persons/km^2, respectively, and decline at higher levels of population density. As Appendix C show, the average partial effect (APE) of a 100 person per km^2 increase in population density is roughly a 13% and 5% increase in mean fertilizer and purchased inputs use per hectare. This total effect of population density on input use intensity is broken down into direct and indirect effect components in Appendix C. However, because of the non-linear relationship between population density and input intensification, partial effects vary across the population density distribution. Appendix C shows direct, indirect and total partial effects of population density on input use intensity at different percentiles in the population distribution. The negative coefficient on the interaction term between population density and distance to motorable roads in the fertilizer intensification model implies that the longer the distance, the lesser is the effect of population density on fertilizer intensification. Similarly, the significant negative interaction term between population density and household landholding in the intensity of purchased input model means that the larger the landholding, the lesser is the effect of population density on purchased inputs intensification. Besides population density and input factor prices, other variables associated with greater intensity of fertilizer and other cash inputs are the price of fertilizers (negatively), distances to roads (negatively), and the age and educational attainment of the household head (positively), the length of the growing period and elevation (both positively).

Impact of population density on the net value of farm output per hectare

Table 7 presents the regression results of the impact of population density on farm output per hectare owned and per

Table 6
CRE estimation results for intensity of cash inputs and fertilizer use per hectare cultivated.

	Log of fertilizer use (KSh)/ha		Log of purchased inputs (KSh)/ha	
	Coef.	$P > z$	Coef.	$P > z$
Population density (100 pp/sq km)	0.284	0.00	0.204	0.00
Population density square	−0.023	0.00	−0.014	0.00
Expected maize price (KSh/kg)	0.413	0.27	0.312	0.10
Land owned (ha)	−0.057	0.22	−0.020	0.42
Wage rate ('00 Ksh/day)	−0.145	0.00	−0.036	0.03
Land rental rates ('000 Ksh/ha)	−0.110	0.00	−0.012	0.40
DAP price (KSh/50 kg)	−0.010	0.01	−0.012	0.00
Distance to motorable road (km)	−0.087	0.00	0.013	0.22
Gender of head (1 = male; 0 = female)	−0.031	0.72	0.046	0.22
Household size	−0.012	0.22	−0.005	0.32
Age of head (years)	0.008	0.01	0.003	0.12
Education attainment of head (years)	0.015	0.07	0.010	0.02
Length of Growing Period (LGP)	0.003	0.01	0.002	0.00
Elevation: meters above sea level	0.088	0.00	0.109	0.00
Slope: measure of steepness – degrees	−0.063	0.01	0.007	0.51
Pop. density*landholding	−0.009	0.52	−0.016	0.04
Pop. density*distance to motorable road	−0.014	0.03	−0.001	0.89
First stage population density residuals	0.002	0.67	0.004	0.09
_cons	0.762	0.57	3.233	0.00
Observations	5845		5845	
Number of households	1169		1169	

Note: Time averages of time varying variables, naïve price expectation of other crop prices, and agroecological zone dummies and survey dummies included.

Table 7
CRE estimation results for net farm production.

	Dep. var: log of farm production (kg)/ha owned		Dep. var: log of farm output (kg)/unit of labor	
	Coef.	$P > z$	Coef.	$P > z$
Population density (100 pp/sq km)	0.282	0.00	0.186	0.00
Population density square	−0.020	0.00	−0.014	0.00
Expected maize price (KSh/kg)	0.002	1.00	0.014	0.54
Land owned (ha)	0.121	0.15	−0.194	0.00
Wage rate ('00 Ksh/day)	−0.156	0.00	−0.315	0.01
Land rental rates ('000 Ksh/ha)	−0.074	0.07	−0.010	0.71
DAP price (KSh/50 kg)	0.004	0.73	0.004	0.54
Rainfall '00 mm	−0.005	0.99	0.079	0.00
Rainfall stress	−0.902	0.00	−0.384	0.06
Own radio (1 = yes; 0 = no)	0.379	0.00	0.166	0.00
Distance to motorable road (km)	−0.028	0.02	−0.054	0.00
Gender of head (1 = male; 0 = female)	0.245	0.06	−0.007	0.92
Household size	0.005	0.78	0.003	0.79
Age of head (years)	0.003	0.53	0.007	0.03
Education attainment of head (# of years)	−0.003	0.83	0.016	0.05
Length of Growing Period (LGP)	0.003	0.09	0.006	0.00
Elevation: meters above sea level	0.334	0.17	0.943	0.00
Slope: measure of steepness – degrees	−0.032	0.21	−0.047	0.03
Pop. density*landholding	−0.030	0.37	−0.141	0.00
Pop. density*distance to motorable road	−0.006	0.03	−0.013	0.01
First stage population density residuals	0.015	0.07	−0.008	0.08
_cons	7.270	0.00	3.975	0.06
Observations	5845		5845	
Number of households	1169		1169	

Note: Time averages of time varying variables and naïve price expectation of other crops included.

family laborer. The net value of farm production per hectare owned is found to rise with population density up to 705 persons/km^2 and decline thereafter (Table 7). This relationship between population density and value of output per hectare is positive and significant up to the 75th percentile of the population density distribution. An increase in population density by 100 persons/km^2 raises mean farm production per hectare by about 14% directly and by 4% indirectly through the effects of increasing population density on prices and landholding sizes. The negative interaction term between population density and distance to the nearest motorable roads means that the longer the distance, the lesser is the effect of population density on farm intensification. Other factors shown to influence farm output per hectare from the results in Table 7 include agricultural wage rates, land rental rates, rainfall stress, ownership radio, distance to motorable roads, the gender of household head, and the length of growing period.

As shown earlier in this section, a regression of households' land under fallow on population density among other covariates revealed that increasing population density reduces mean land under fallow. This signifies a form of intensification of questionable sustainability as households resort to more continuous cultivation

Table 8
CRE estimation results for total household income and off-farm income.

	Log income (KSh)/adult equivalent		Log off-farm income (KSh)/adult equivalent	
	Coef.	$P > z$	Coef.	$P > z$
Population density (100 pp/sq km)	−0.037	0.02	0.079	0.10
Expected maize price (KSh/kg)	0.021	0.20	−0.005	0.82
Land owned (ha)	0.188	0.00	0.049	0.33
Wage rate ('00 Ksh/day)	−0.032	0.02	−0.018	0.60
Land rental rates ('000 Ksh/ha)	−0.043	0.03	−0.005	0.86
DAP price (KSh/50 kg)	−0.008	0.10	0.003	0.67
Rainfall '00 mm	−0.010	0.45	0.026	0.20
Rainfall stress	−0.024	0.84	0.227	0.19
Own radio (1 = yes; 0 = no)	−0.218	0.00	0.123	0.02
Distance to motorable road (km)	−0.019	0.02	−0.001	0.77
Gender of head (1 = male; 0 = female)	0.206	0.00	0.421	0.00
Household size	−0.101	0.00	−0.066	0.00
Age of head (years)	0.029	0.91	−0.009	0.01
Education attainment of head (# of years)	0.023	0.00	0.022	0.02
First stage population density residuals	0.018	0.59	−0.008	0.10
_cons	8.738	0.00	8.625	0.00
Observations	5845		5845	
Number of households	1169		1169	

Note: Time averages of time varying variables, naïve expectation of other crop prices, and survey year and agroecological zone dummies included.

and reduced fallow periods in response to increasing population density. As shown earlier, results also show evidence of more sustainable and positive land intensification (e.g. increased expenditures on fertilizer and other cash inputs) at least up to roughly 700 persons/km^2.

A somewhat less favorable picture emerges when we consider farm intensification defined as farm production per unit of family labor (Table 7). Family labor is defined as the number of adult equivalents in the household adjusted by the number of months in the past year spent in residence at the household. Farm production increases with population density up to 664 persons/km^2 and drops thereafter. In this case a significant portion of the rural population (roughly 20%) resides in areas exceeding 655 persons/km^2. A 100 person per km^2 rise in population density increases the net value of farm output per unit labor by 9% directly and by 3% indirectly through the effect of the increasing population density on prices and landholding size. The negative and significant coefficient on the interaction term between population density and distance to the nearest motorable implies that the longer the distance, the lesser is the effect of population density on crop intensification. Besides population density and prices, other important factors that are associated with the net value of farm output per unit of family labor are the amount of rainfall expected and rainfall shocks, distance to motorable roads, household demographic characteristics and the agricultural potential of the area where the household is located.

Relationship between population density and household off-farm and total income

Results in Table 8 show that population density is positively associated with off-farm income although the coefficient is only significant at the 10% level of significance. An increase in population density from the 25th to the 75th percentile of the distribution (i.e. from 204 to 598 persons/km^2) is associated with an increase in mean household off-farm income of 32%. Other important correlates of household off-farm income are found to be households' access to information and demographic variables. For example, a switch from male to female headship is associated with a 42% reduction in household off-farm income. Similarly, relatively smaller households, households headed by younger persons, and those headed by persons with high educational attainment earn more off-farm income.[13]

Finally, we examine the relationship between population density and total household income. Total household income per adult equivalent is found to be a linear declining function of population density (Table 8). An increase in population density by 100 persons/km^2 reduces household's mean income directly by 4% and indirectly by 3% through the influence of population density on factor prices and landholding (Appendix C). Appendix C also shows population partial effects on household income at different percentiles of the population density distribution. Other important factors influencing the level of household incomes include access to information, distances to input and output markets, and household demographic variables. While ownership of a radio increases mean household income by about 22%, increased distances to motorable roads reduce income by about 2%. A switch from male to female headship reduces household income by 21%, while each additional year of the household head's educational attainment is associated with a roughly 2% increase in total household income.

Conclusions and policy implications

The overarching objective of this study was to examine how rising population pressure in rural Africa is affecting the evolution of smallholder farming systems and agricultural intensification. The study is motivated by the need to understand the nature and magnitude of emerging land constraints in African agriculture, using Kenya as a case study. Kenya's increasingly densely populated rural areas characterize a rising proportion of Africa's rural population, and hence this study may provide clues about the future challenges that other African countries will face in the next several decades. Using a five-round panel covering the 1997–2010 period, we investigate how increasing rural population density over this period has affected farm household behavior.

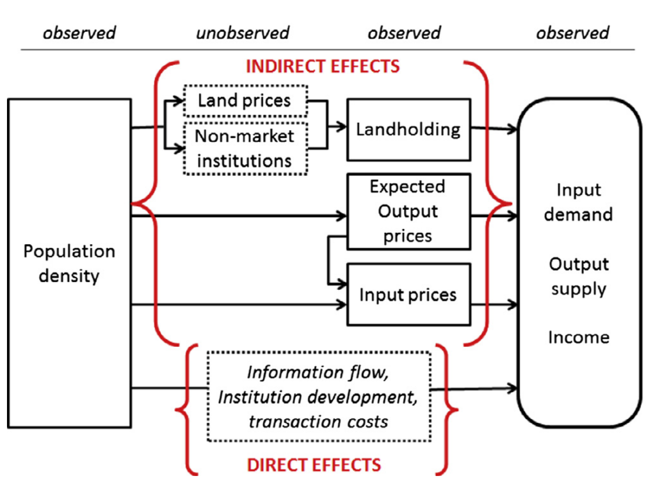
[13] These findings are consistent with qualitative evidence gathered during initial field work indicating a rise in low paying jobs in the densely populated areas such as sale of used clothing (*mitumba*); cellphone money transfer services (*M-Pesa*); cellphone repairing and battery charging; buying of old household materials such as scrap metal; bicycle passenger transport (*boda-boda*) services; and repairing and hawking of household utensils (*mali-mali*).

The overall picture emerging from our findings is that land is becoming an increasingly constraining factor of production for a sizeable and growing proportion of Kenya's rural population. Rising population density is found to be associated with shrinking farm sizes and cultivated areas. Fortunately, rising population densities are contributing to land intensification and increases in the net value of crop production per unit of land and labor – at least up to roughly 550–600 persons/km^2. The increases in land intensification appear to be occurring in forms that are favorable to sustainable intensification – e.g. increased use of cash inputs and shifts to higher valued crops – as well as forms of intensification that are not sustainable, including more continuous cultivation and reductions in fallows without adequate nutrient replenishment and soil restoration, consistent with other research findings from Kenya (e.g. Pender et al., 2006; Fermont et al., 2009; Powlson et al., 2011).

We also find that rising population density influences household behavior and farming systems indirectly through changes in relative factor prices. Rising population density increases the price of the scarce factor (land) relative to agricultural labor. A reduction in the land–labor ratio induces innovations aimed at intensifying the use of land, consistent with the induced innovation theories of Boserup (1965) and Ruttan and Hayami (1971). However, our results indicate that agricultural labor productivity does not rise with population density in a linear fashion. For the 20% and growing percentage of Kenya's rural population residing in areas exceeding 550–600 persons/km^2, the net value of crop output per labor unit declines with increased population density. This would not be a great problem if off farm income were able to absorb excess rural labor into the non-farm sectors, but unfortunately we find a relatively low response of off-farm income to increased rural population density. While our results do not explain the reasons for the decline in agricultural intensification beyond the threshold of 500–600 persons/km^2, it is very plausibly associated with soil mining/degradation as a result of continuous cultivation and congestion in the densely populated areas (Drechsel et al., 2001; Tittonell and Giller, 2012). Using cross-country African data, Drechsel et al. (2001) found an inverse relationship between population density and soil carbon and other soil nutrients levels that strongly influence the average products of fertilizer use in crop production. The smaller size of farms in densely populated areas may also impede households' ability to produce a surplus, which in turn impedes their ability to finance cash input purchases associated with land intensification. The population density thresholds found in this study coincides with the maximum land supporting capacity for areas of intensive crop cultivation in the region as found by Henao and Baanante (1999).

These results also indicate that smallholder landholding sizes are gradually declining in Kenya as in much of sub-Saharan Africa. Generally, these findings lead to policy questions about appropriate and feasible smallholder-led agricultural strategies in the context of land-constrained farming systems. One could conclude that the only way out of poverty for the severely land-constrained rural poor is to increase their access to land. Viewed from this perspective there is some scope for promoting equitable access to land through land redistribution reforms to reduce landholding inequalities. A coordinated strategy of public goods and services investments in road infrastructure, schools, health care facilities, electrification and water supply would be helpful in raising the economic value of arable land in the country that is relatively remote and still unutilized. However, viewed within a dynamic structural transformation framework, this group's brightest prospect for escape from poverty will most likely involve being pulled off the farm into productive non-farm sectors. Farming will be increasingly unable to sustain the livelihoods of people born in rural areas without substantial shifts in labor from agriculture to non-farm sectors. Education, which played a crucial role in Asia by allowing households to exit agriculture into more lucrative off-farm jobs, is relatively low in most areas of rural Africa by world standards. Investments in rural education and communications are likely to become increasingly important to facilitate structural transformation. However, there are no assurances that non-farm will grow fast enough to be able to absorb all the surplus rural labor. And in fact, our findings from Kenya indicate that off-farm incomes are not increasing significantly with population density. An important long-run goal will be to pull the rural poor out of agriculture and into skilled off-farm jobs through public investments and policies that support urban job creation and the processes of structural transformation. Increasing emphasis on education, health, and integration with the broader global economy are likely to be especially important in attracting private investment to Africa's non-farm sectors and providing viable jobs to attract the region's largely underemployed work force into productive non-farm jobs. A young, healthy, and relatively well-educated work force would certainly help promote this process.

Appendix A. Effects of human population density on smallholder production and income



Source: Chamberlin (2013).

Appendix B. Summary statistics of main variables used in the estimations

Variable	Mean	p10	p25	p50	p75	p90
Net crop production ('000 KSh)	67.66	3.52	12.49	31.69	78.94	162.36
Net farm production ('000 KSh)	83.84	6.40	18.20	44.65	100.69	193.17
Off-farm income ('000 KSh)	72.43	0.00	5.00	28.10	84.00	180.40
Aggregate household income ('000 KSh)	167.70	21.32	49.33	103.28	201.50	368.24
Fertilizer application (kg/ha)	55.13	0.00	0.00	34.48	79.44	138.62
Purchased inputs use ('000 KSh/ha)	13.48	2.63	5.01	9.44	16.82	29.02
Land rental rates ('000 KSh/ha)	2.29	1.00	1.20	2.00	3.00	4.00
Agricultural wage rate (KSh/day)	87.08	45.00	60.00	75.00	100.00	128.57
Farm-gate maize price (KSh/kg)	13.93	8.89	11.11	13.33	15.56	21.11
Household landholding (ha)	2.40	0.40	0.80	1.30	2.50	5.30
Households land under cultivation (ha)	1.40	0.30	0.50	1.00	1.70	2.80
Land under fallow (ha)	1.00	0.10	0.30	0.30	0.80	2.50
Population density (persons/km^2)	440	103	204	412	598	874
Distance to nearest motorable road (km)	0.84	0.01	0.10	0.30	1.00	2.00
Distance to nearest water source (km)	5.54	0.00	0.20	2.00	7.00	15.00
Distance to nearest health center (km)	3.32	0.80	1.50	2.50	4.00	7.00
Distance to the nearest electricity supply (km)	4.09	0.10	0.70	2.00	4.50	9.00
Proportion of households owning a bicycle	0.46	0.00	0.00	0.00	1.00	1.00
Proportion of households owning a radio	0.85	0.00	1.00	1.00	1.00	1.00
Storage facility value ('000 KSh)	4.87	0.00	0.00	0.00	3.0	15.00
Proportion of households headed by males (%)	0.80	0.00	1.00	1.00	1.00	1.00
Age of the household head (years)	55.93	38.00	46.00	56.00	66.00	74.00
Household head's education attainment (years)	6.35	0.00	3.00	7.00	10.00	12.00
Household size (people)	5.96	2.50	4.00	5.83	7.75	9.58
Length of Growing Period (LGP)	282	135	255	315	345	350
Elevation ('000 m above sea level)	1.68	1.18	1.46	1.67	1.94	2.11
Slope: measure of steepness (degrees)	4.63	1.33	2.49	4.09	5.92	8.67
Proportion of women that can read and write in the division	0.39	0.27	0.33	0.38	0.46	0.55
Proportion of Catholics in the division	0.35	0.22	0.33	0.35	0.41	0.42
Average age of women at first marriage in the division	17.88	17.20	17.26	18.04	18.18	18.49
Proportion of women using contraceptive in the division	0.29	0.11	0.17	0.28	0.40	0.44
Average age of women at first marriage in the division	17.28	16.41	16.46	17.18	18.02	18.41
Average age of women at first intercourse in the division	27.99	21.31	22.45	28.61	31.02	34.90
Average number of children died per woman in the division	0.73	0.19	0.43	0.75	1.02	1.06
Household head's fathers landholding (ha)	16.60	0.00	3.00	7.00	19.00	37.00
Spouse's fathers landholding (ha)	11.16	0.00	1.00	5.00	12.00	30.00

Appendix C. summary of population density effects on agricultural systems and income

	Effects	Average partial effects	Partial effects at percentiles of the population density distribution				Population density turning point
			25th	50th	75th	90th	
Wage rate (KSh/day)	Direct	−0.196	−0.24	−0.21	−0.17	−0.12	1104
Land rental rate (KSh/ha)	Direct	0.021	0.08	0.06	0.02	0.01	1138
Land owned (ha)	Direct	−0.159	−0.159	−0.159	−0.159	−0.159	–
Area under cultivation (ha)	Direct	−0.169	−0.169	−0.169	−0.169	−0.169	–
Area under fallow (ha)	Direct	−0.186	−0.186	−0.186	−0.186	−0.186	–
Fertilizer use (KSh)/ha	Direct	0.125	0.196	0.143	0.082	−0.010	617
	Indirect	0.006	0.005	0.005	0.005	0.005	
	Total	0.132	0.202	0.149	0.087	−0.005	
Value of purchased inputs (KSh)/ha	Direct	0.094	0.14	0.10	0.07	0.02	729
	Indirect	−0.041	−0.06	−0.06	−0.06	−0.06	
	Total	0.053	0.08	0.05	0.01	−0.04	

(continued on next page)

Appendix C (*continued*)

	Effects	Average partial effects	Partial effects at percentiles of the population density distribution				Population density turning point
			25th	50th	75th	90th	
Value of crop production (KSh/ha owned)	Direct	0.135	0.156	0.133	0.105	0.065	645
	Indirect	0.037	0.037	0.037	0.037	0.037	
	Total	0.171	0.193	0.169	0.142	0.101	
Farm production (kg)/ha owned	Direct	0.140	0.179	0.130	0.074	−0.010	705
	Indirect	−0.018	−0.018	−0.018	−0.018	−0.018	
	Total	0.121	0.160	0.112	0.056	−0.028	
Farm output (kg)/unit of labor	Direct	0.087	0.197	0.163	0.123	0.065	664
	Indirect	0.028	0.028	0.028	0.028	0.028	
	Total	0.114	0.224	0.190	0.151	0.093	
Income (KSh)/adult equivalent	Direct	−0.037	−0.037	−0.037	−0.037	−0.037	–
	Indirect	−0.030	−0.030	−0.030	−0.030	−0.030	–
	Total	−0.067	−0.067	−0.067	−0.067	−0.067	–
Off-farm income (KSh)/adult equivalent	Direct	0.079	0.079	0.079	0.079	0.079	–

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