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How does population density influence agricultural intensification and productivity? Evidence from Malawi

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ABSTRACT

This article uses nationally representative household-level panel data from Malawi to estimate how rural population density impacts agricultural intensification and household well-being. We find that areas of higher population density are associated with smaller farm sizes, lower real agricultural wage rates, and higher real maize prices. Any input intensification that occurs seems to be going to increasing maize yields, as we find no evidence that increases in population density enable farmers to increase gross value of crop output per hectare. We also find evidence that households in more densely populated areas increasingly rely on off-farm income to earn a living, but there appears to be a rural population density threshold beyond which households can no longer increase off-farm income per capita.

Introduction

Boosting agricultural production in the face of a growing population is one of the major challenges facing Sub-Saharan Africa (SSA) at the start of the 21st century. However, to date few empirical studies attempt to estimate the extent to which population density affects agricultural intensification and household well-being. This is a critical issue because current population estimates in SSA stand at 856 million people, and the United Nations projects that the region's population could increase to 2 billion by 2050 under their medium growth scenario (United Nations, 2011; Bremner, 2012). While cereal yields increased by 1.8% per year on average across the continent between 2000 and 2010 (FAOSTAT, 2012), in most SSA countries population growth averages above 2% per year, and tops 3% per year in a number of countries (World Bank, 2013). The disparity between yield increases and population growth raises doubt about how millions of smallholder farm households will feed themselves, and how the food system in SSA can generate enough surplus to feed the non-agricultural population. This is particularly the case as the amount of additional arable land that can be brought into cultivation continues to decline and is already non-existent in some areas.

It is against this background that this study was conducted using household-level panel data from Malawi with the objective to estimate how rural population density affects both agricultural intensification, and household well-being. Other important studies have discussed agricultural intensification in SSA in the context of rising population density (Boserup, 1965; Binswanger and McIntire, 1987; Pingali and Binswanger, 1988; Pender, 1998; Pender et al., 2006). In particular, Pender et al. (2006) use household-level panel data for Ethiopia, Kenya, and Uganda to compare how agricultural intensification and well-being are affected along the gradient of agricultural potential, market access and population density.

In this article, we define agricultural intensification at the household-level in terms of input usage and productivity. Specifically, we estimate (1) demand for inorganic fertilizer per hectare of land cultivated, (2) maize yield, and (3) gross value of crop output per hectare of land cultivated. Well-being is measured as (1) off-farm income per adult equivalent, (2) total household income per adult equivalent.[1] We measure population density in this study

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[1] Adult equivalents are created to normalize the nutritional needs of different family members in a household based on age and gender. The conversion calculations for adult equivalents in this study come from the World Health Organization (1985), and are available from the author upon request.

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as persons per square kilometer of land using population estimates from the Global Rural Urban Mapping Project (GRUMP), available from the International Food Policy Research Institute (IFPRI) website (http://www.ifpri.org/dataset/global-rural-urban-mapping-project-grump).[2]

Malawi is an ideal case study because it is a densely populated country with an estimated 15 million people, whereby 85% of the population lives in rural areas and derives its livelihood from agriculture. There is a substantial regional variation in population density, with the majority of the population concentrated in the central and southern regions, while the north remains sparsely populated. It is estimated that Malawi's population will reach 20.8 million by 2020 (NSO, 2008). As Malawi has little room for expanding area under cultivation, agricultural production must intensify in order to produce enough food for the growing population.[3,4]

In this study we empirically test Boserup's (1965) hypothesis that increasing population density leads to increased input use per unit of land, and increased production per unit of land as farmers move successively from long fallow to short fallow, to annual cropping, and finally to multiple cropping cycles per year. The related *induced innovation* hypothesis predicts that as population grows, farmers will substitute away from labor saving practices like slash and burn agriculture and long follow, and adopt labor and capital intensive practices such as inorganic fertilizer and hybrid seed which maximize output per unit of land (Hayami and Ruttan, 1971).

Critically, this article also tests whether or not there is a population density threshold beyond which the Boserupian and *induced innovation* hypotheses do not apply, as farmers are no longer able to intensify production through using modern inputs. Intensification will not proceed beyond the point at which its marginal cost exceeds the marginal returns. Even in high density areas, marginal returns to purchased inputs may be insufficient to rationalize their use. This may be especially true in high-density areas of longstanding continuous cultivation where soil degradation (particularly diminished soil organic matter) may have given rise to poor responsiveness to inorganic fertilizer applications (Drechsel et al., 2001). Given limited access to technology and capital faced by many smallholders, such limits may be further accentuated by high fixed costs of new technology discovery and adoption. Inability to intensify will lead to lower incomes, assets and lack of credit availability, which makes it difficult for farmers to purchase modern inputs and increase yields and farm output. The existence of thresholds raises the question of whether or not structural transformation in Africa may decelerate, or break down altogether, as rural densities approach critical levels.

In this study we hypothesize that population density affects agricultural intensification and household well-being through both *direct* and *indirect* channels. The *direct* effects come through supply and demand forces such as increased information flow, development of markets and institutions, and reductions in transaction costs that may occur as a result of increased population density. McMillan et al. (2011) show that communities with high population density in Burkina Faso have more developed formal and informal institutions than areas of low population density. Pender (1998) introduces a neo-classical growth model to the issue of population density, and finds that increasing population leads to the development of markets, and institutions, along with the substitution of natural capital for man-made capital.

The *indirect* channels through which population density affects agriculture and household well-being come from its effect on landholding, agricultural wage rates, and output prices. Landholding, wage rates and prices then in turn directly affect agricultural intensification, and household well-being. Since land markets are very thin and underdeveloped in Malawi and in most of SSA, we would expect to see the impact of population growth reflected in household landholding, rather than through land prices.[5] *Ex ante*, population growth should lead to smaller farm sizes, as land gets divided over time and as households move from long fallow, to short fallow, to annual cropping, to multiple cropping cycles per year, as hypothesized by Boserup. We would also expect that agricultural wage rates will decline in areas of high population density, as the number of workers increases relative to the amount of land, as predicted by the *induced innovation* hypothesis. The relationship between declining wage rates and rising population density will certainly depend on the extent to which rural agricultural markets are integrated with local non-farm markets and urban labor markets. In addition, in a closed economy with limited land we would expect to see rising population lead to rising prices for staple crops like maize, as more and more people compete for food. Conversely, in a small open economy higher population density may not affect food prices (other than perhaps in the short run), as food can be brought in from elsewhere to meet demand, other things being equal.

Data used to measure the effect of population density on agricultural production and household well-being in this analysis come from three main sources. First, we use three waves of nationally representative household-level panel data collected between 2003 and 2009 by Malawi's National Statistical Office. Second, we use Geographic Information Systems (GIS) data to construct village-level estimates of population density, elevation and agricultural productivity factors in Malawi. Third, we compliment the quantitative data with qualitative information on population growth and its impact on agriculture and livelihoods, from focus group discussions conducted across Malawi during October 2011.

In this study we recognize that population density may be endogenous in our models of agricultural intensification and household well-being. We deal with the potential endogeneity of population density by first including a rich set of explanatory variables that control for household characteristics, market access, and agro-ecological potential. Second we use the correlated random effects estimator (CRE) to control for potential correlation between population density and the unobserved time-constant factors that affect our outcomes of interest. Nevertheless, as with any study using observational data on household behaviour, assuming direct causality from our results must be treated with caution.

Results from our analysis demonstrate that in Malawi areas of high rural population density are associated with a reduction in farm sizes, lower real agricultural wage rates, and higher real

[2] We use GRUMP rather than AfriPop data (as used by other case studies in this special issue) because in the case of Malawi, the spatial resolution of the input data is much better for GRUMP. GRUMP uses population data from 9219 Enumeration Areas (about 3 km^2 on average), whereas AfriPop uses input data from just 253 Traditional Authorities. While the input data for GRUMP are from 1998 and the input data for AfriPop are from 2008, we felt that the benefits of increased spatial resolution of input statistics were greater than having more recent input data. In addition, since the first year of our data was collected in 2003 it makes sense to have population estimated based on an *ex ante* rather than *ex post* estimate. In practice, however, this probably matters little, since the 2010 projections vary little between the AfriPop and GRUMP datasets for the villages in our study.

[3] For nearly a decade, the Government of Malawi has been implementing the farm input support program (FISP) to mainly boost maize and tobacco production. The presence of a large-scale input subsidy program is an example of an important institutional reform that can impact intensification, and well-being. Fortunately with our data, we are able to control for the input subsidy program's possible effect of the outcomes of interest in this article.

[4] Malawi's annual population growth rate is estimated to be 2.9% (World Bank, 2013).

[5] The vast majority of land in Malawi is held under customary tenure, with only a very small percentage being leased or owned by farmers (National Statistical Office, 2011). While antecdotal evidence suggests that land sale transactions are rare, there is evidence to suggest that land rental markets in Malawi are fairly active. For example, the data used in this analysis indicate that in the 2008/09 rainy season 24% of respondents either rented out or rented in land.

maize prices. We also find some evidence that increases in population density encourage farmers to intensify fertilizer use per hectare. However, any input intensification that occurs seems to be going to increasing maize yields, as we find no evidence that increases in population density lead to increases in gross value of crop output per hectare. This could be due to a decline in tobacco prices and/or a shift towards maize for food security purposes and away from other more high-value crops. We also find evidence that households in more densely populated areas increasingly rely on off-farm income as a source of livelihood. However, there appears to be a rural population density threshold beyond which households can no longer increase off-farm income per capita.

The rest of this article is organized as follows. The next section presents the background on population, land and agriculture in Malawi. Then the conceptual framework and methods used in the analysis are presented. Subsequent sections present the data, results and conclusions.

Background

Population issues in Malawi

Rural population densities in Malawi vary considerably across different regions of the country. According to estimates using the GRUMP with observations from our dataset, northern Malawi has a median population density of 69 people/km^2, and contains 13% of the country's population. The central region is estimated to have a median population density of 194 people/km^2, containing 42% of the nation's population. The densely populated southern region is estimated to have a median population of 258 people/km^2, and contains 45% of the nation's population (see Table 1).[6]

Table 1
Distribution of population density (persons/km^2 of land) by region. *Source:* Authors' calculations based on the Global Rural Urban Mapping Project (GRUMP) database.

Region	Mean	10th	25th	50th	75th	90th
North	129	37	63	69	119	483
Central	190	98	116	194	250	295
South	262	151	218	258	340	375
Total	217	77	126	221	278	346

Land issues in Malawi

In Malawi, it is widely believed that about 30,000 agricultural estate farms cover around 1.2 million ha, while 1.8–2 million smallholder farms cover about 4.5 million ha. The rest of the land is covered by public land, hills, steep slopes, wetland and protected areas (Government of Malawi, 2002; Chirwa, 2008). Access to land is generally regarded as key for sustainable livelihoods in Malawi. Scholars view land access as a significant determinant of whether a household will be food secure, less vulnerable to risks and shocks, and earn a living above the poverty line (Woodhouse, 2006; Potts, 2006). Nevertheless, the existing land tenure system and pattern of land use is the result of antecedent customs, human settlement and demographic processes, modified by legal and economic influences of the colonial era, and previous policies on land utilization. As a result, land ownership in Malawi is highly unequal. For instance it is estimated that 70% of smallholder farmers cultivate less than a hectare with a median area under cultivation of 0.6 ha. Smallholders in Malawi devote most of their land to maize cultivation, the country's main staple crop, with tobacco serving as the country's main cash and export crop.

Institutions affecting landholding in Malawi

Most of the laws governing land administration and management in Malawi were formulated while the country was a British Colony between 1891 and 1964. These laws have remained the same apart from minor amendments since independence, and as a result the current land policy in Malawi is very similar to the policy under colonial rule (Gondwe, 2002). The essence of colonial land policy in Malawi was to appropriate all land to the British sovereign and to facilitate access by the settler community on the basis of private title. The policy also redefined native rights strictly as "occupation rights" in order to discourage the establishment of land rights equivalent to freeholds or the concessions claimed by the settlers.

A series of land ordinances and laws since the 1950s have done little to improve the land tenure system in Malawi as it moved from British colony to independent one-party government under Hastings Kamuzu Banda, who ruled Malawi from independence to 1994. Multi-party democratization in the 1990s offered opportunities to address a whole range of inequities and injustices perpetrated by the one party regime, including inequitable land redistribution patterns (Kishindo, 2004; Kanyongolo, 2005). Although land reform and re-distribution has been identified as needing immediate action, land policy in Malawi has overall failed to address these issues. As a result, land ownership is essentially the same today as it was during the colonial era. For all practical purposes, most smallholder land remains "customary" land where allocation rights are granted to farmers by local chiefs. Smallholders have limited ability to hold land in title, not to mention buy, sell or rent land. This lack of land tenure insecurity and immobility undoubtedly contributes high levels of rural poverty in Malawi today.[7]

Input subsidies in Malawi

Subsidies for in organic fertilizer and seed have existed in one form or another for many years in Malawi. However, after a poor harvest during 2004/05 that was in part affected by drought, the government of Malawi decided to scale up their fertilizer and seed subsidy the following year. Officially the program distributes 100 kg of subsidized fertilizer and between 2 and 4 kg of hybrid maize seed to roughly 50% of the smallholders in Malawi. The fertilizer and seed are distributed via vouchers, where recipient farmers can redeem subsidized fertilizer at government depots for a reduced price (the subsidy has range from a 72% discount to a 92% discount off of the commercial price of fertilizer during the years of the subsidy program).[8]

The general findings from the recent empirical literature on input subsidies in Malawi are that they have had a statistically significant, but small effect on maize production, and that from a benefit-cost perspective, the programs barely break even.[9] Nevertheless, the scaling-up of input subsidies in Malawi over time represent an important institutional change that needs to be considered in our analysis.

Conceptual framework and methods

This section presents the framework to understand and estimate how population density effects landholding, wage rates,

[6] Official estimates from Malawi's National Statistical Office (NSO) indicate that the southern region has a population density of 185 people/km^2. The central region has a population density of 154 people/km^2, and the northern region has a population density of 63 people/km^2 (National Statistical Office, 2008).

[7] For more information on land tenure issues in Malawi see Chirwa (2008).

[8] In 2005/06 and 2006/07 farmers could redeem their vouchers at selected private retailers. From 2007/08 subsidized fertilizer has only been redeemable at government depots, while subsidized seed has been available from private dealers in all years.

[9] For a thorough review of input subsidies in Malawi see Dorward and Chirwa (2011) and Lunduka et al. (2013).

maize prices, agricultural intensification and household well-being.

Conceptually, we start by modelling a farm household in a non-separable context that is assumed to maximize utility as a function of on-farm and off-farm activities. The input decisions that a household makes are a function of the household-level and community-level constraints that it faces. For example, its decision to apply in organic fertilizer is affected by household-level factors such as access to credit, labor availability, and how much subsidized fertilizer and seed a household acquires. Degree of market access, and population density are examples of community-level factors that impact fertilizer demand. Population density could have a direct impact on *fertilizer demand* through its effect on supply and demand for agricultural goods. For example, it is possible that population density affects information flows and transaction costs of market participation. In more densely populated areas it may be easier to find transaction partners, market information, etc., thus causing the costs of input and output market participation to be directly affected by local density.

Given these constraints when considering household utility maximization, the first derivative of utility for household i in community j at time t with respect to output price generates the following output supply equation for maize produced per hectare. This is denoted by Y in the following equation:

$$Y_{ijt} = \alpha_1 D_j + \alpha_2 D_j^2 + \beta P_{ijt} + \Upsilon w_{ijt} + \rho L_{ijt} + \mathbf{X}_{ijt}\delta + \varepsilon_{ijt} \tag{1}$$

where population density and its squared term are defined by D, while α_1 and α_2 represent the corresponding parameters. The significance and magnitude of the coefficients $\hat{\alpha}_1$ and $\hat{\alpha}_2$ test the hypothesis of how population density and its squared term *directly* affect maize production per hectare. The squared term in D allows us to test if population density has a non-linear threshold effect, where output starts to decrease after a certain critical level of population density.

Previous season maize price is denoted by P, while β represents the corresponding parameter. Agricultural wage rate is denoted by w, and Υ represents the related parameter. In a standard output supply function, input and output prices are the only factors that influence Y. However, in the context of a non-separable farm household model such as the one presented for Malawi, other factors such as landholding, household demographics, weather and agronomic conditions also impact output supply (see Appendix A for a full list of explanatory variables). Landholding is represented by L in this application, with ρ as the relevant parameter to be estimated. The other demographic and agronomic variables that serve as controls, such as household assets, household demographics, kilograms of subsidized fertilizer acquired, and rainfall, are represented by the vector $\mathbf{X}$, and δ represents the corresponding parameter vector.[10] The unobservable factors that affect Y are represented by ε.

The models for estimating the other measures of agricultural intensification and well-being are operationalized in a completely analogous manner as output supply for maize in Eq. (1).

Population density landholding, wage rates and maize prices

We present separate models for household landholding, L, wage rates w, and maize prices, P as functions of the following:

$$(L_{ijt}, w_{ijt}, P_{jt}) = \alpha_1 D_j + \alpha_2 D_j^2 + \mathbf{X}_{ijt}\delta + \mu_{jit} \tag{2}$$

where D again represents population density in level and squared form, and α represents the corresponding parameter. The significance and magnitude of the coefficients $\hat{\alpha}$ tests the hypothesis of how population density and its squared term affect landholding size, wage rates, or maize prices in their respective models. A vector of time-varying household-level factors, such as value of assets, demographics, and agronomic conditions are again denoted by $\mathbf{X}$, while δ represents the corresponding parameter vector. The error term in Eq. (2) is represented by μ.

As population grows, one would expect land to be divided into smaller and smaller plots as it is passed down from parents to children. Therefore, ex ante it would seem that $\hat{\alpha}_1$ should have a negative sign in the landholding specification. At the same time, the induced innovation theory implies that as population grows, land becomes scarce relative to labor *ceteris paribus*. As a result we might expect $\hat{\alpha}_1$ to also have a negative sign in the wage rate model.

As mentioned in the introduction, in a closed economy rising population could lead to rising prices for maize. Conversely, in a small open economy higher population density will not affect food prices (other than perhaps in the short run), as food can be brought in from elsewhere to meet demand. The recent literature on market integration and price transmission in southern Africa is generally consistent in finding that markets are reasonably well-integrated, and are becoming more so over time (Rashid, 2004; Awudu, 2007; van Campenhout, 2008; Myers and Jayne, 2012). However, there are areas where markets are not fully integrated and local supply and demand factors may matter. Also, in Malawi maize often moves from the sparsely populated and surplus producing north to the high population density and deficit producing south.[11] Therefore, we might expect $\hat{\alpha}_1$ to be positive in the maize price model, however the magnitude of the effect of population density on maize prices will in part depend on the degree of spatial market integration in Malawi.

Estimating the indirect effects of population density

We hypothesize that population density has both a *direct* and *indirect* effect on household-level intensification, and well-being. The *indirect* effect of population density on these indicators comes from population densities direct influence on landholding, agricultural wage rates, and maize prices. Landholding, wage rates, and prices then in turn affect agricultural intensification, and household well-being. Therefore, if we want to estimate the impact of population density D on maize output per hectare, Y in Eq. (1), consider the equation for Y as,

$$Y_{ijt} = \alpha_1 D_j + \alpha_2 D_j^2 + \beta P_{jt}(D_j) + \Upsilon w_{ijt}(D_j) + \rho L_{ijt}(D_j) + \mathbf{X}_{ijt}\delta + \varepsilon_{ijt} \tag{3}$$

[10] It is possible that the quantity of subsidized fertilizer and/or subsidized seed acquired by the households may be endogenous in our models, because the variable could be correlated with unobservable factors like ability and motivation that affect the outcomes of interest in our study. Several recent studies have addressed this issue (see Ricker-Gilbert et al., 2011; Mason and Ricker-Gilbert, 2013). In the present study we use the correlated random effects estimator (discussed in the next section), which controls for the endogeneity of subsidized fertilizer acquisition to the extent that it is correlated with time-constant unobservable factors, such as farmer ability and motivation. We do not give extensive treatment to this issue in this paper because the subsidy is not the focus of this study, and we include the input subsidy in our models to act as a control for institutional factors that have changed over time in Malawi.

[11] Another issue associated with estimating a maize price model in Malawi is the impact that the pan-territorial maize price set by the parastatal marketing board, The Agricultural Development and Marketing Corporation (ADMARC) has on retail market maize prices. A recent study finds that ADMARC price positively affects retail maize prices, and the Granger causality test shows that the causation is one way (Mapila et al., 2013). ADMARC price effects are a major issue when conducting a time-series analysis such as in Mapila et al. However, the present study uses only three waves of data, and since the ADMARC price is pan-territorial we would not be able to identify its effect, because the price does not vary spatially. The ADMARC pan-territorial price would be the same as a year fixed effect, which we deal with by including year dummies in our model.

Combining population density and its squared term in D create the equation for the total derivation for Y with respect to D as:

$$\frac{\partial Y_{ijt}}{\partial D_j} = \alpha + \left[\frac{\partial Y_{ijt}}{\partial P_{jt}} * \frac{dP_{jt}}{dD_j}\right] + \left[\frac{\partial Y_{ijt}}{\partial w_{ijt}} * \frac{dw_{ijt}}{dD_j}\right] + \left[\frac{\partial Y_{ijt}}{\partial L_{ijt}} * \frac{dL_{ijt}}{dD_j}\right] \tag{4}$$

The resulting derivative is the Average Total Partial Effect (ATPE). The ATPE tells us the combined *direct* and *indirect* effect that population density and its square term have on the measures of agricultural intensification and household well-being. The coefficient estimate $\hat{\alpha}$ provides the *direct* effect of population density on Y, while the sum of the remaining three terms estimates the *indirect* effect of population density on Y through its direct effect on landholding, agricultural wage rates, and maize prices. The ATPE of population density on the other measures of intensification and well-being are derived in an analogous manner.

Empirical estimation: dealing with potential endogeneity of population density

We deal with the potential endogeneity of population density using a correlated random effects estimator (CRE) to control for possible correlation between observed covariates, in particular population density D, and the unobserved time-constant factors that affect the dependent variables in the analysis. These factors are unobservable to us as researchers but could include farmer motivation, risk aversion, and ability. To control for this possible relationship we disaggregate the error term in Eq. (1) into two components:

$$\varepsilon_{ijt} = b_{ij} + \zeta_{ijt} \tag{5}$$

where b_i denotes the unobserved time-constant heterogeneity and ζ_{it} represents the unobserved time-varying shocks. The CRE estimator operates under the assumption that the unobserved heterogeneity takes on the form of $b_{ij} = \varphi_{ij} + \overline{X}_{ij}\xi + r_{ijt}$ and that $r_{ijt}|\overline{X}_{ij} \sim Normal(0, \sigma^2)$; where $\overline{X}_{ij}$ is the household time average of X_{ijt} of all time-varying covariates in Eqs. (1) and (2). To operationalize the CRE estimator + $\overline{X}_{ij}$ needs to be included as a covariate in all equations. When implemented as a linear model the CRE estimator controls for unobserved heterogeneity, and produces coefficient estimates that are identical to those generated by household-level fixed effects (Wooldridge, 2010). An added benefit of the CRE estimator over fixed effects is that the CRE does not remove time-constant covariates from the models. This benefit is very important because we are interested in understanding the long-run effect of population density, which is treated as fixed over time in this application.

The fact that the CRE allows us to keep time-constant covariates in our model matters because the time frame in which we are examining the impacts is relatively short, between 2003 and 2009, so the variation in population density will mainly occur spatially between one community and another. It is also difficult to accurately measure spatial changes in population density over such a short time period. Fortunately, our dataset provides ample spatial variation because 99 enumeration areas were surveyed in each of the three waves of data collection. The CRE estimator allows us to keep population density in our model even though it is treated as time-constant, whereas a fixed-effects or first-difference estimator will drop population density and other time-constant factors from the model.

In addition, we maintain that the time-varying unobservable shocks, ζ_{ijt}, that affect agricultural intensification and household well-being are uncorrelated with population density. After conditioning on household factors, and community factors, and, using the CRE, population density should be conditionally exogenous in our models of agricultural production and household well-being. Even with this consideration in mind, the relationships in this study should be looked at as correlations more than as causal effects.

Estimation procedure Seemingly Unrelated Regression (SUR)

The estimation procedure used in this study takes place as follows: The models in Eqs. (1) and (2) are estimated as a linear system using Seemingly Unrelated Regression (SUR) with CRE. The benefits of using SUR is that it allows us to account for the fact that these equations are likely determined jointly, causing the errors in each equation to be correlated with one another. Therefore, SUR provides an efficiency gain over CRE equation by equation, because it explicitly controls for cross-equation error correlation. We present results using CRE SUR estimation rather that CRE equation-by-equation, because the coefficients are virtually the same and the SUR estimation is more efficient.

Data

Data used in this article come from three main sources. First we use nationally representative household-level data on smallholder farmers in Malawi. Second, GIS data is used to construct the population density and arable land variables used in the analysis. Third, we use qualitative data from focus group discussions conducted throughout Malawi during October 2011.

Panel survey data

Household-level data used in this study come from three surveys of rural farm households in Malawi. The first wave of data comes from the Second Integrated Household Survey (IHS2), a nationally representative survey conducted during the 2002/03 and 2003/04 growing seasons that covers 26 districts in Malawi, and interviewed 11,280 households. The second wave of data comes from the 2006/07 Agricultural Inputs Support Survey (AISS1), conducted during the 2006/07 growing season. The budget for AISS1 was much smaller than the budget for IHS2 and of the 11,280 households interviewed in IHS2, only 3485 of them lived in enumeration areas that were re-sampled in 2006/07. Of these 3485 households, 2968 were re-interviewed in 2006/07, which gives us an attrition rate of 14.8%.

The third wave of data comes from the 2008/09 Agricultural Inputs Support Survey II (AISS2) conducted during the 2008/09 growing season. The AISS2 survey had a subsequently smaller budget than the AISS1 survey in 2006/07, so of the 2968 households first sampled in IHS2 and again in AISS1, 1642 of them lived in enumeration areas that were revisited in AISS2. Of the 1642 households in revisited areas, 1375 were found for re-interview in AISS2, which gives an attrition rate of 16.3% between AISS1 and AISS2. For this analysis we use the 1375 households who were interviewed in all three waves of data, which results in 4125 observations in total. In this study, potential attrition bias is controlled to the extent that (i) attrition is correlated with the observed covariates; and (ii) the CRE is used to control for time-constant unobserved factors that affect both the outcomes of interest and household attrition across survey waves.

Geospatial data for constructing population density and agro-ecological variables

GIS data on rural population densities are derived from the Global Rural–Urban Mapping Project database (GRUMP) (Balk and Yetman, 2004). The GRUMP dataset represents a significant improvement over coarser estimates of population density often used in econometric work (e.g. tables of regional population density estimates), for two reasons. First, GRUMP uses the most localized unit of geographic record which is the enumeration area (EA), and there are 9219 EA's in Malawi. Second, the urban and rural components of population distributions have been disaggregated on the basis of statistical data as well as satellite-derived information on the distribution of urban centers (Balk and Yetman, 2004). This allows us to specifically account for rural population density, rather than total population density, which is much less relevant to our research question. The population density estimates are constructed as people per square kilometer of total land.[12]

In addition, we use a number of other geographical controls derived from spatial datasets. Locally interpolated time-series data on rainfall come from the University of East Anglia's Climate Research unit (CRU)-TS 3.1 Climate Database (CRU, 2011; Mitchell and Jones, 2005). Data on historical rural population come from the HYDE dataset (Goldewijk et al., 2011). Net Primary Productivity (NPP) data come from the University of Montana (Zhao et al., 2005).[13] Elevation data are obtained from NASA's SRTM data (Rodriguez et al., 2005).

Focus group discussions

Apart from the use of secondary data in this study, the researchers carried out Focus Group Discussions (FGDs) with a number of communities to get an insight into their land and population issues. Seven areas were visited with three in the southern part of the country, two in the central and the other two in the north of the country. One site that was visited in the southern part of the country was the community that benefited from the Land Reform Program commonly called "Kudzigulira Malo." These areas visited include Chatheka Extension Planning Area (EPA) in Nkhata Bay, Mhuju EPA in Rumphi, Mkanda EPA in Mchinji, Lobi EPA in Dedza, Ntimbawe Trust in Machinga, Kwisimba Ilage village of Maiwa EPA in Mangochi, Chibwana and Ngongoliwa villages in Thyolo.

Fertilizer prices[14]

Fertilizer prices used in the study are calculated as Malawian Kwacha per kilogram of commercial fertilizer from the household survey data. The price is an average of Urea and Nitrogen/Phosphorus/Potassium (NPK) prices, which are the main fertilizers used in Maize cultivation in Malawi. These prices are based on what respondents in the survey say they paid for commercial fertilizer at private retailers during the planting season, which occurs from October to December in Malawi. For those buying commercially we use the observed price that they paid, while for those who did not buy commercially we use the district median price to proxy for the price that the farmer faces for the input.

Labor wage rates

Wage rates for labor hired by households on their plot are calculated as Malawian Kwacha per day of labor. In the survey we only have wage rates for hired in labor and have no way to value family labor other than to include a variable for the number of adult equivalents in the household as a proxy for the number of people that are potentially able to work, in the model. For those who hire in labor, we use the price that they pay, while for those who do not hire in labor, we use the district median price to proxy for the price that the farmer faces for the input.

Maize prices

Data for the maize price variable used in this study come from district-level data on maize retail sales, collected by the Malawian Ministry of Agriculture.

Landholding and area cultivated

Landholding is constructed using the household survey data based on the amount of land that farmers say that they have the right to cultivate. It is computed as the sum of crop land, fallow land, virgin land, orchards, and land rented out, but excludes land rented in. Landholding is used as a dependent variable in Eq. (2), and as a right hand side variable in the intensification and well-being models.

We construct area cultivated as the amount of land that a household cultivates for rainy season crop production during the corresponding year. This calculation includes land rented in but not land rented out. Area cultivated is used as the denominator for the dependent variables for the intensification measures.[15]

The use of farmer recall data to calculate landholding and area cultivated likely creates measurement error as farmers often do not know the exact size of their plots. However, in the case where measurement error is part of the dependent variable (e.g.: when landholding is the dependent variable in Eq. (2)), or when area cultivated is in the denominator of the dependent variable in Eq. (1)) we can still obtain consistent results if the measurement error in area cultivated has a zero mean and is uncorrelated with right hand side (RHS) variables. Even if the measurement error does not have zero mean, the bias caused by it will be picked up by the intercept term (Wooldridge, 2010). In addition, if the classic error in variables assumption holds, meaning that we assume measurement error in landholding is uncorrelated with actual landholding, then there may be attenuation bias in the models where landholding is a RHS variable. In this situation the coefficient estimates on landholding should be regarded as lower bound estimates.

Gross value of crop output

This measure of intensification is measured as the gross value of what a household produces during the rainy season per hectare cultivated. The crop is valued at harvest time (May–July in Malawi). To construct this variable, we multiply the quantity produced by the median price in the community for that crop at harvest time and divide by area cultivated.

[12] We chose total land as our denominator for population density, because this definition of land is subject to the lowest amount of interpolation, and the estimates of population density are similar to readers' expectations (see Table 1). We also, ran the models where population density is estimated as people per square km of arable land, which includes currently cultivated land plus potentially cultivatable land, according to the GRUMP data. The results using the arable land definition are generally similar to our base specification, but the coefficient magnitudes are a bit different, and fewer coefficients are statistically significant using the arable land definition. When population is divided by arable land the population density estimates increase substantially, (mean = 429 people/km^2 of arable land, and some rural population density estimates over 2100 people/km^2), which is unrealistic. Results using this alternative definition of population density are available from the authors upon request.

[13] Net primary productivity is a measure of the rate at which chemical energy is stored as biomass in a given period. It is a useful proxy for agricultural production potential in a particular area. In the dataset we use in this analysis, NPP is measured as the mass in grams of carbon per square meter per year.

[14] All prices are in real 2009 Malawi Kwacha terms. US \$1.00 $\approx$ 150 Malawi Kwacha during survey periods.

[15] Note that the correlation between landholding and area cultivated is 0.79 in our dataset. Median landholding and area cultivated are both 0.81 ha, while mean landholding is 1.07 ha, and mean area cultivated is 0.98 ha. NSO 2011 estimates that during the 2009/10 growing season, the average area cultivated per rural household in Malawi was 1.5 ha when estimated by GPS.

Controlling for family labor

Family labor is not reported directly at the plot level in the survey. This is potentially an issue because family labor is likely the largest source of labor for many rural households in Malawi. However, we know how many family members are in the household and their age, so the best we can do is include a measure for adult equivalents to proxy for potential available labor in the household. Adult equivalents is also useful because it proxies for caloric and nutritional requirements of the household. The calculation for adult equivalents is explained in Footnote 1.

Results

Descriptive results

Figs. 1–6 show non-parametric lowess smoothing estimates of the relationship between population density on the *X*-axis and some of the key dependent variables used in this analysis on the *Y*-axis. These relationships are bi-variate and unconditional, and as such should be regarded as providing useful descriptive information, but they are not *ceteris paribus* effects. For context, the dotted lines show the 25th, 50th, 75th, and 99th percentile of the population density distribution in our sample.

Fig. 1 presents the relationship between rural population density and household landholding. The figure shows that landholding sizes decline with rising densities up to about 380 people/km^2, which is the 95th percentile of the population density distribution. Fig. 1 points to land being an increasingly constrained factor of production in smallholder agriculture in the high-density areas of Malawi. The general results of the graph are consistent with our focus group discussions, which highlight the issue that in many areas particularly in southern Malawi land cannot be expanded. This exacerbates poverty levels and food insecurity in areas of high population density. The focus group discussions also revealed that in some areas farmers are able to rent land, however there is virtually no market for buying or selling land. Lack of a functioning land market exacerbates the problem related to small farm sizes in densely populated areas.

Fig. 2 shows the relationship between population density and real agricultural wage rates. According to the figure wage rates decline as population density increases up to a population density of about 400 people/km^2, which is about the 96th percentile of the population density distribution, at which point wages shoot upward. This could be the result of urbanization driving up wages, and further disaggregation reveals some interesting findings. The central region has the highest jump in wage rates at high population density, and 78% of the high wage earners who make more than 300 kwacha/day are located in the densely populated Lilongwe district or the Kasungu district. In the North, 77% of the high wages are in the less densely populated Karonga and Chitipa districts, which is what we would expect. The densely populated south has no clear bi-variate pattern between wage rates and population density. Overall, the relationship between population density and agricultural wage rates is what we might expect, as

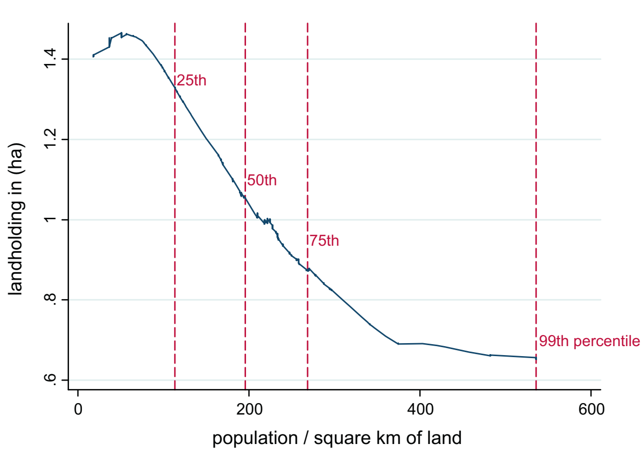

Fig. 1. Household landholding by population density.

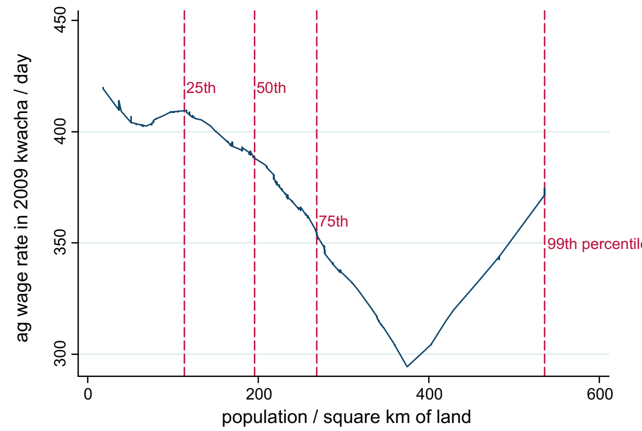

Fig. 2. Real ag. wage rate, by population density.

Fig. 3. Real retail maize price, by population density.

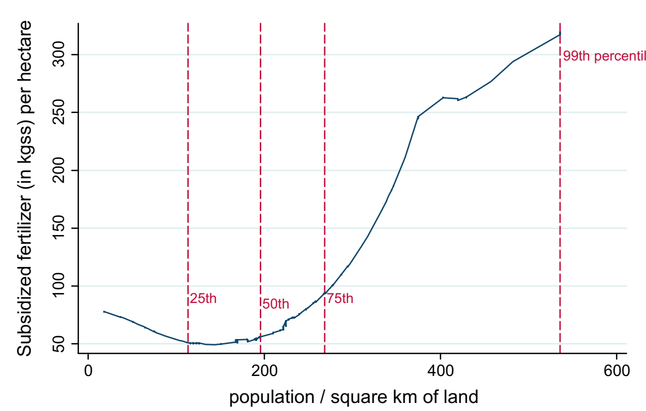

Fig. 4. Kilogram of subsidized fertilizer used/ha, by population density.

Fig. 5. Kilogram of commercial fertilizer used/ha, by population density.

Fig. 6. Gross value of crop output/ha, by population density.

low density areas have large land holdings but few adults per hectare, and therefore higher wages are needed to attract labor.

Fig. 3 presents the relationship between population density and real retail-level maize prices during the harvest season, which runs from May through July in Malawi. This bivariate figure suggests that maize prices rise substantially as population grows, up to nearly the 75th percentile of population density, when it flattens out. The price of maize fluctuates by about 21% at 24 kwacha/kg in low density areas to 29 kwacha/kg in high density areas. These results may be driven by maize moving from the sparsely populated and surplus producing north to the high population density and deficit producing south. Moving maize across the country involves price mark-ups which can help explain higher prices in areas of higher population density.

As land becomes scarce, one might expect farmers to increase input intensification in order to improve production per hectare. In the Malawian context this effect is also influenced by the input subsidy program. Fig. 4 shows household subsidized fertilizer use per hectare by population density. The figure indicates that after the 50th percentile, subsidized fertilizer acquisition rises with population density. This finding provides some *prima facia* evidence that the subsidy program may help farmers in highly density areas intensify production, or at least maintain some base level of productivity as landholdings shrink and soils degrade. Focus group respondents in high population density areas complained of degraded and infertile soil, caused by continuous cropping. In fact, Malawi has extremely high soil erosion rates and severe nutrient mining, due to its geography independent of population density (Drechsel et al., 2001).

Fig. 4 can be compared with Fig. 5 showing commercial fertilizer use per hectare, by population density. The figure indicates that households increase commercial fertilizer purchase from about the 25th percentile to about the 95th percentile, before decreasing drastically at very high levels of population density. This turning point may exist because farmers in these areas likely have small landholding, meaning that they likely lack the assets or collateral to acquire credit for purchasing inputs. However, Fig. 5 is generally consistent with the idea of population density driving intensification through acquisition of purchased inputs.

Fig. 6 demonstrates that as population density increases, gross value of crop output per hectare cultivated is flat at low level of population density and then increases. This provides some evidence that households may intensify production or switch to higher valued crops in areas of high population density. This upward trend is also consistent with higher maize prices in areas of high population density.

Fig. 7 shows that the value of off-farm income per adult equivalent appears to be higher in areas of high population density. This could be because households in high density areas have surplus labor, which they hire out. The finding also relates to migration issues, which was one of the other key points that came out of the focus group discussion. As mentioned, the northern region of Malawi has significantly more available land than the central and southern regions of the country. However, there is very little internal migration from the central and south to the north. Our focus group discussion revealed that migration is limited because (1) many Malawian smallholders lack the resources required for migration to distant areas; (2) public health and education services are poor in the north, which discourages in-migration; (3) road infrastructure and market access for commodities is very weak in the north, which also discourages in-migration; (4) cultural differences between people in northern and southern Malawi are a barrier to in-migration from other regions. These differences make it hard for someone from the south to move to northern Malawi and obtain land to farm.

Fig. 8 shows the bivariate relationship between total household income per adult equivalent and population density. The figure demonstrates a nearly linear increase in total household income per adult equivalent as population density rises. Since the graph in Fig. 8 is similar to the graph in Fig. 7 showing the relationship between off-farm income per adult equivalent and population density, these two graphs together may provide some *prima facia* evidence that gains in total household income in areas of higher population density are driven by off-farm employment. However,

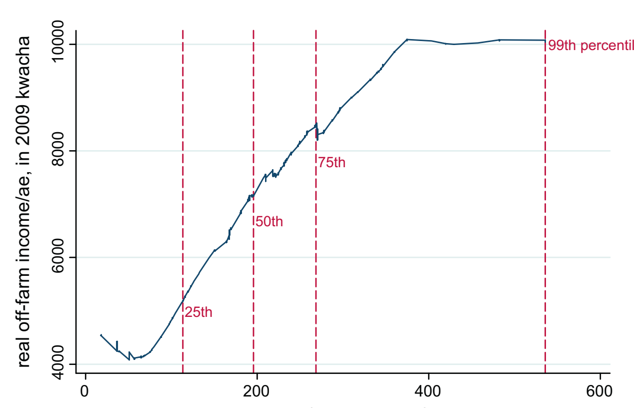

Fig. 7. Real off-farm income/adult equivalent, by population density.

the trend in Fig. 8 continues upward at high levels of population density while the trend line in Fig. 7 flattens out. Therefore, some gains to household income in areas of high population density could also be coming from on-farm activities. This would be consistent with Fig. 6, which shows that gross value of crop output per hectare increases at high levels of population density.

Evidence that off-farm activities are more prevalent and total household income per adult equivalent is higher in areas of high density raises the question of whether or not people in densely populated rural areas are being "pushed" into off-farm work because farms are too small for agriculture to be viable. Conversely, are people being "pulled" into off-farm work by new opportunities that may arise from reduced transactions costs and market development occurring in areas of higher population density (Haggblade et al., 2009)? Fig. 9 suggests that unfortunately people in densely populated areas of Malawi are engaged in off-farm activities that offer little opportunity for economic advancement. The figure shows the share of income in 2008/09 generated by household activities other than cultivating crops during the rainy season. It demonstrates that 44% of households' other income comes from employment, primarily through working as piece-meal agricultural labor, known as *ganyu* in Malawi. Another 20% of non-rainy season crop income comes from household enterprises. On the surface this sounds promising but deeper analysis of the data reveals that many of these enterprises are low skill endeavours such as petty trading, selling firewood, and fishing. Some of these activities such as selling firewood may provide short term profits, and allow households to survive from season to season, they provide little opportunities for households to sustainable improve their situation in the long run. Gifts from others also make up another 8% of non-rainy season crop income, while social safety net programs comprise 6%.

The type of activities that seem to hold more promise for economic advancement make up a relatively small share of household income. Dry season and tree cultivation make up 9%, livestock sales make up 7%, and livestock product sales make up 1%. Other income sources which comprise rental income, investments, and remittance income make up 5%. While these numbers provide insight into a worrying situation for household activities outside of rainy season crop cultivation, they also provide information about opportunities for government to intervene with programs that can enhance dry season cultivation and animal agriculture in order to improve household income and well-being.

Estimation results

The following sub-sections present the results for factors affecting landholding, wage rates, maize prices, agricultural

Fig. 8. Real total household income/adult equivalent, by population density.

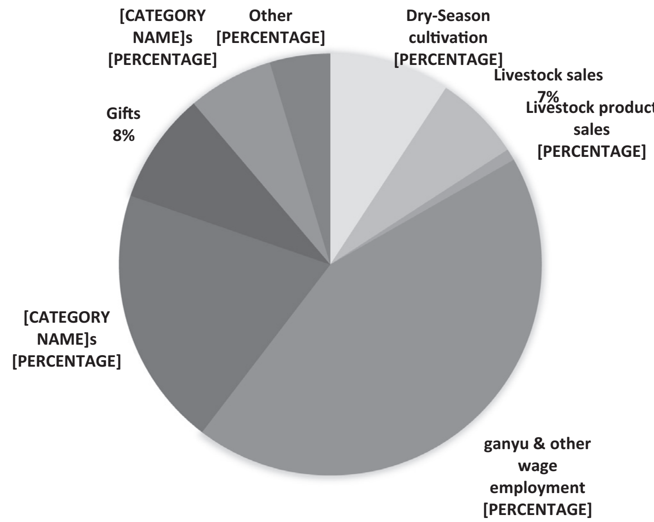

Fig. 9. Share of income from sources other than rainy-season crops during 2008/09 season.

intensification, and household well-being. As mentioned in the methodology section, these models are estimated by correlated random effects (CRE) Seemingly Unrelated Regression (SUR).

Determinants of landholding size

Column 1 of Table 2 allows us to test the hypothesis of how population density affects household landholding measured in hectares. The results shown in column 1 indicate that the joint direct effect of population density and population density squared on landholding is statistically significant (p-value = 0.00). The coefficient estimate shows that a 100 person increase in people per square kilometer is associated with a reduction in landholding of 0.12 ha on average. This is a fairly meaningful finding in Malawi because farm sizes are very small, with a mean landholding of 1.2 ha. Therefore, a 100 person increase in population density reduces mean farm size by about 10%. Considering the fact that land is regarded as the key input for poverty reduction and food security (Woodhouse, 2006; Potts, 2006),[16] the decline in farm size associated with landholding points to a troubling picture. Focus group respondents in densely populated areas reiterated their desperation caused by shrinking farm sizes. The respondents who were part of Malawi's voluntary land reform program indicated that the main reason for moving was to acquire more land. In fact, recent empirical evidence suggests that these voluntary land redistribution programs help participants increase food production (Mueller et al., forthcoming). These findings highlight the need for the government to make it easier for households to buy, sell, and rent land.

Determinates of wage rates

Column 2 of Table 2 presents determinates of real daily agricultural wage rates. Wage rates are estimated in log form so the coefficients should be interpreted as semi-elasticities. Column 2 demonstrates that population density and its squared term have a statistically significant effect on agricultural wage rates. The p-value on population density is (0.01), and on its square term

[16] The coefficient on population density is negative and the squared term is positive and close to being statistically significant, which initially may indicate that as population density increases landholding declines up to a certain point and then the effect levels out. However the turning point on the squared term in column 1 of Table 2 indicates that the negative relationship does not change until population density reaches 533 people/km^2, which is at the 99th percentile of the population density distribution, so the turning point likely has little real meaning.

Table 2
Factors affecting landholding, wage rates, and maize prices.

Covariates	(1) Landholding		(2) Log ag. wage rates		(3) Log maize price	
	Coeff.	*p*-Value	Coeff.	*p*-Value	Coeff.	*p*-Value
Population density * 10[a]	−0.020***	(0.00)	0.0092***	(0.01)	0.0021**	(0.02)
Population density^2 * 10[a]	1.840E−05	(0.11)	−1.790E−05***	(0.00)	−3.33E−07	(0.84)
Fertilizer price	–	–	−0.205**	(0.00)	−0.036***	(0.00)
Household landholding	–	–	0.027**	(0.02)	–	–
=1 if farm credit organization in village[a]	−0.0713**	(0.02)	0.080***	(0.00)	−0.032***	(0.00)
Distance to paved road[a]	0.001**	(0.03)	1.964E−04	(0.57)	−6.710E−04***	(0.00)
Distance to main district market[a]	0.003***	(0.00)	−7.755E−04***	(0.00)	4.078E−04***	(0.00)
Real total value of household assets	–	–	3.740E−08	(0.32)	–	–
Age of household head[a]	0.009**	(0.05)	0.001	(0.63)	–	–
Age of household head^2 [a]	−3.280E−05	(0.45)	−1.200E−05	(0.61)	–	–
=1 if household head attended school[a]	0.147***	(0.00)	0.005	(0.77)	–	–
=1 if household headed by female	−0.154**	(0.03)	0.039	(0.32)	–	–
Household adult equivalent	0.069***	(0.00)	−0.005	(0.50)	–	–
Death of household head or spouse, past 2 yrs	0.065	(0.51)	−0.066	(0.21)	–	–
Average of growing season rainfall, past 20 years	−1.120E−04	(0.35)	1.800E−05	(0.78)	−1.507E−04***	(0.00)
CV past 20 year rainfall	−5.096***	(0.00)	1.871***	(0.00)	−0.978***	(0.00)
Net primary productivity[a]	−2.73E−05***	(0.00)	1.510E−05***	(0.00)	2.130E−06***	(0.01)
Elevation[a]	4.351E−04**	(0.04)	3.445E−04***	(0.00)	−1.454E−04***	(0.00)
Elevation^2[a]	−3.660E−07***	(0.00)	−2.830E−07***	(0.00)	3.600E−08**	(0.05)
Population Density Turning Point	533		257		3144	
Direct effect: APE of population density + pop density^2 * 10	−0.012***	(0.00)	0.002*	(0.10)	0.002***	(0.00)
Observations	4125		4125		4125	
R^2	0.18		0.41		0.87	

Notes: p-values in parentheses; model includes time averages of time-varying covariates, year dummies, district dummies, and a constant.
*** The corresponding coefficients are statistically significant at the 1% level.
** The corresponding coefficients are statistically significant at the 5% level.
* The corresponding coefficients are statistically significant at the 10% level.
[a] Time-constant factor that does not vary over time, and only changes spatially.

the *p*-value is (0.00). The joint direct effect of population density and its square, near the bottom of column 2 is marginally statistically significant. The coefficient indicates that a 10 person increase in population density is associated with a 0.2% increase in average agricultural wage rates. This effect is relatively modest on average, but the individual coefficients tell a more interesting story. They indicate that agricultural wages rise as population increases up to a density of 257 people/km^2, after which wages start to decline. The turning point occurs near the 70th percentile of the population density distribution, and the concave relationship may indicate that wage rates get bid up at low levels of population density as labor is a relatively scarce resource. Once a certain level of population density is reached however, wage rates decline as labor becomes cheap relative to land. The concave relationship between population density and wage rates found in column 2 of Table 2 is essentially the opposite finding from the concave relationship found in Fig. 2. The reason for this difference could be due to the fact that the regression results in Table 2 control for supply side factors such as distance to market and paved roads which likely affect how easy it is for agricultural workers to find jobs.

Determinates of maize price

Column 3 of Table 2 presents the factors affecting the log of retail maize prices. Just as with wage rates the coefficients should be interpreted as semi-elasticities. Results from the joint direct effect of population density and its square term, near the bottom of column 3, indicate that a 10 person increase in population density increases retail maize prices by 0.2% on average (*p*-value = 0.00). The effect of population density is fairly modest, but any increase in food price has a significant impact on poor households in Malawi who are generally net consumers of maize and are often forced to buy maize at market to make up for their own-farm production shortfalls (Dorward, 2006; Alwang and Siegel, 1999). The regression results are consistent with the bivariate relationships in Fig. 3, and as mentioned earlier this relationship may be driven by maize moving from the sparsely populated and surplus producing north to the high population density and deficit producing south.[17]

Determinates of household-level intensification

Column 1 of Table 3 presents the determinants of demand for inorganic fertilizer, measured as kilograms purchased by the household per hectare. The results from column 1 show that population density and its square term each have individually statistically significant *direct* effects on fertilizer demand. However, **row I** near the bottom of column 1 shows that the joint *direct* effects of population density and population density squared are not statistically significant. This finding indicates that the direct supply and demand effects of population density, through improved information flow, market development, and transaction cost reductions are not associated with an increase in fertilizer demand in Malawi. **Row II** of column 1 shows that the *indirect* effects of population density on fertilizer demand per hectare which operate through its effect on landholding, wage rates and maize prices are statistically significant and positive (*p*-value = 0.02). The coefficient indicates that an increase in population density of 10 people/km^2 is associated with an increase in fertilizer demand of 0.15 kg/ha on average. This finding provides some evidence that the *indirect* pathways of population density have a small positive effect on fertilizer demand. For example, it could be that the *indirect* effects of declining farm sizes caused by rising population density force households to intensify fertilizer use in an attempt to improve maize cultivation for food

[17] The turning point in the relationship between population density and its squared term is statistically significant, but the turning point is well outside the range of our data at 3144 people/km^2.

Table 3
Factors affecting household-level intensification.

Covariates	(1) Fertilizer demand/ha cultivated		(2) Maize yield/ha cultivated		(3) Gross value of crop output/ha cultivated	
	Coeff.	*p*-Value	Coeff.	*p*-Value	Coeff.	*p*-Value
Population density * 10[a]	−1.65**	(0.02)	−10.14*	(0.08)	−3138	(0.31)
Population density^2 * 10[a]	0.004***	(0.00)	0.002**	(0.05)	8.7	(0.13)
Real retail maize price	−13.89	(0.28)	−97	(0.38)	−54,517	(0.36)
Fertilizer price	−17.98**	(0.01)	151**	(0.01)	18,955	(0.56)
Agricultural wage rate	−14.34***	(0.00)	−88***	(0.01)	−4070	(0.82)
Household landholding	−16.67***	(0.00)	−105***	(0.00)	−124	(0.99)
Kilograms of subsidized improved maize seed acquired	−0.08	(0.61)	0.65	(0.65)	125	(0.87)
Kilograms of subsidized fertilizer acquired	0.50***	(0.00)	1.84***	(0.00)	40	(0.70)
=1 if farm credit organization in village[a]	6.86**	(0.04)	71**	(0.01)	−5209	(0.73)
Distance to paved road[a]	0.001	(0.99)	−1.21**	(0.04)	−286	(0.36)
Distance to main district market[a]	−0.005	(0.92)	−1	(0.21)	51	(0.83)
Real total value of household assets	1.540E−05**	(0.04)	1.08E−04*	(0.10)	0.006	(0.86)
Age of HH head[a]	−0.93*	(0.05)	−2	(0.57)	769	(0.72)
Age of HH head^2[a]	0.007	(0.13)	0.01	(0.76)	−13	(0.53)
=1 if household head attended school[a]	4.75	(0.19)	63**	(0.04)	−37,731**	(0.02)
=1 if household headed by female	−2.12	(0.79)	−18	(0.79)	−25,651	(0.48)
Household adult equivalent	−2.60	(0.11)	36***	(0.01)	−274	(0.97)
Death of HH head or spouse, past 2 yrs	−12.07	(0.26)	−58	(0.52)	248,489***	(0.00)
Avg. growing season rainfall, past 20 yrs	0.02	(0.14)	–	–	–	–
Coef. of variation past 20 year rainfall	62.72	(0.53)	–	–	–	–
Cum. rainfall over current growing season, in cm	–	–	0.19**	(0.01)	−30**	(0.47)
Net primary productivity[a]	−4.39E−04	(0.49)	−0.01***	(0.01)	−2	(0.50)
Elevation[a]	0.16***	(0.00)	1***	(0.00)	22	(0.83)
Elevation^2[a]	−4.74E−05***	(0.00)	−4.47E−04***	(0.01)	0.002	(0.97)
Population Density Turning Point	Direct Effect not stat sign.		Direct Effect not stat sign.		Direct Effect not stat sign.	
I. Direct Effect: APE of pop. density + pop. density^2 * 10	0.06	(0.81)	−1.41	(0.51)	415	(0.30)
II. Indirect Effect: APE of population density through landholding, wages, and mz price * 10	0.15**	(0.02)	0.92**	(0.04)	−115	(0.46)
III. Total Effect: ATPE, direct + indirect * 10	0.21	(0.41)	−0.49	(0.83)	300	(0.29)
Observations	4006		4006		4006	
R^2	0.30		0.13		0.02	

Notes: APE = average partial effect, ATPE = Average total partial effect. *p*-Values in parentheses; model includes time-averages of time-varying covariates, year dummies, district dummies, and a constant.
*** The corresponding coefficients are statistically significant at the 1% level.
** The corresponding coefficients are statistically significant at the 5% level.
* The corresponding coefficients are statistically significant at the 10% level.
[a] Time-constant factor that does not vary over time, and only changes spatially.

security. The total effect in **row III** of column 1 shows that the combined *direct* and *indirect* effect of population density on fertilizer demand is positive but not statistically significant.

Column 1 also demonstrates that households with more assets and access to credit in their village purchase more fertilizer. Households with more land demand less fertilizer per hectare, which likely indicates that they farm less intensively than households who farm smaller landholdings. Column 1 also shows that an extra kilogram of subsidized fertilizer increases total fertilizer use per hectare by 0.50 kg on average. This effect is statistically significant (*p*-value = 0.00), but relatively small in magnitude. It is consistent with other studies in Malawi that have found evidence of subsidized fertilizer crowding out commercial fertilizer (Ricker-Gilbert et al., 2011; Jayne et al., 2013). The presence of a farm credit organization in the village leads to higher fertilizer use, by likely reducing households' credit constraints.

Column 2 of Table 3 presents the factors affecting maize yield. Population density and its squared term each have statistically significant individual effects on maize yield. However, **row 1** at the bottom of column 3 shows that the joint *direct* effects of population density and its squared term are not statistically significant, indicating that supply and demand effects such as increased information and reduced transactions costs are not driving increases in maize yield. Conversely, **row II** shows that the *indirect* effects of population density are statistically significant (*p*-value = 0.04). The coefficient indicates that a 10 person increase in population density is associated with households producing about 0.92 kg more maize per hectare, on average. Since the average maize yield in our data is 808 kg/ha, this effect is relatively small. However, the statistical significance of the *indirect* effect may signal that households are trying to intensify maize production on a per hectare basis due to shrinking landholdings, and possibly rising maize prices that are a result of increased population density. This finding is consistent with the statistical significance of positive indirect effects of population density on fertilizer demand. The total effect of population density in **row III** is not statistically significant, likely due to the fact that the *direct* effects are not statistically significant. Results from column 3 also show that those households who have more assets are able to generate higher yields, which may help wealthier households offset the negative effects of population density.

Column 2 also shows that an additional kilogram of subsidized fertilizer raises maize production by 1.84 kg on average (*p*-value = 0.00). This effect is positive, and may provide evidence that subsidized fertilizer helps farmers intensify maize output in the face of rising population density and declining farm size. The magnitude of the effect is relatively small, which is consistent with the recent literature on the topic (Lunduka et al., forthcoming). Agro-ecological variables also seem to play a role in determining maize yields. Areas with more rainfall during the growing season obtain higher yields, which is not surprising. Higher elevation areas also have higher yields. In addition, households further from paved roads get lower maize yields, which speaks to the importance of market access. Having a farm credit organization in the village leads to higher yields, likely because it facilitates access to modern inputs.

Column 3 of Table 3 presents factors affecting real gross value of crop output per hectare. This measure provides an estimate of the value of household-level intensification across all crops grown by the household. The results from column 3 indicate that population density does not have a statistically significant *direct*, *indirect* or *total* effect on crop revenue. This may mean that households are not able to switch to higher value crops as population density increases, possibly due to lack of transport and perishability of higher value fruit and vegetables. It could also have to do with the fact that tobacco prices have been low in recent years. Since tobacco is the main cash crop for smallholders in Malawi, low tobacco prices will reduce the value of crop output.

The findings from both columns 2 and 3 of Table 3 provides some evidence that households may focus on maize production as population density rises. Since land available for cultivation is fixed in many high density areas, maize could be crowding out production of other crops. A recent study in Malawi suggests that the input subsidy program may be promoting maize production, which is its goal, at the expense of other crops (Chibwana et al., 2011). The idea that farmer in high density areas may be using the subsidy to produce maize, possibly at the cost of reducing production of other crops is supported by Fig. 4 which shows that households in areas of high density have been acquiring more subsidized fertilizer on a per hectare basis than households in other areas. Households may be emphasizing maize production to ensure their food security, but this could have negative effects on household income and nutrition, if production of other crops are being ignored. It is surprising to note that in column 3 households experiencing a recent adult death have much higher value of crop output per hectare than others. It could be that these households are older, more established and have more land, assets, and income.

Determinates of household well-being

Column 1 of Table 4 presents the factors affecting household off-farm income per adult equivalent. Results show that population density and population density squared each have individually statistically significant *direct* effects on off-farm income per capita. **Row I** at the bottom of column 2 also shows that population density and population density squared have a statistically significant joint *direct* effect on off-farm income per capita (*p*-value = 0.00). The coefficient means that a 10 person increase in population density raises off-farm income by 197 kwacha (roughly US $1.31) on average. Since a 100 person increase in population density is associated with a US $13.10 increase in off-farm income per person the effect while not huge, is fairly meaningful in economic magnitude. It is important to note that the turning point in this relationship occurs at 295 people/km^2, which is about the 85th percentile in the population density distribution. The *indirect* effect is not statistically significant, but the *total* effect largely results from the *direct* effects of population density on off-farm income. The findings from column 2 provide evidence that households in areas of higher population density are turning towards off-farm income to earn a living. This finding is consistent with the descriptive analysis in Fig. 6 that shows rising off-farm income per adult equivalent as population density increases. The fact that most of the increases in off-farm income come from the *direct* effects, which are likely the result of market and institutional development may be an encouraging sign. However, the quadratic relationship indicates that above the 85th percentile of the population distribution, the increases in off-farm income per capita from population density reverse and begin to decline. This could mean that *direct* effects such as market development may not be large enough for households in very high density areas to increase per capita off-farm income. In addition, recall from Fig. 8 that much of the off-farm income for rural households in Malawi comes from menial jobs such as piece-meal agricultural labor, petty trading, and social safety nets.

Column 2 of Table 4 shows the factors influencing total household income per adult equivalent. Results from this column demonstrate that population density and its square term each have individually statistically significant impacts on total household income per capita. The joint *direct* effect in **row I** is also significant (*p*-value = 0.00) and indicates that a 10 person increase in population density raises total household income by 220 Malawi kwacha (roughly US $1.47) on average. This finding has reasonable economic meaning for smallholders, many of whom live on little more than US $1.00 per day. The turning point in this relationship occurs at 350 people/km^2, which is about the 92nd percentile of the population density distribution.

The findings about total household income are similar to the finding on off-farm income in column 1 in Table 4. Our results show that there is some positive impact on household income from population density, but those gains come from off-farm income rather than from intensification in agricultural production. There could be some "pull" factors at play because there may be more off-farm jobs available in areas of high population density through market and institutional development. Conversely, there could be some "push" factors occurring because as population density increases, farm sizes shrink, and agriculture becomes less viable forcing households to turn towards off-farm work to earn a living. It is also important to note that households where the head has attended school have higher income per capita on average then households with uneducated heads, which speaks to the importance of education in providing opportunities to become better farm managers and/or seek better off-farm opportunities.

Conclusions

The objective of this study is to estimate the impacts of rural population density on agricultural intensification and household well-being in Malawi. High population density and access to arable land are widespread issue in Malawi, and are particularly acute in the central and southern part of the country.

Several important conclusions regarding the relationship between population density, intensification, and well-being emerge from this study. First, higher population densities are associated with smaller landholding. At the average landholding size of 1.2 ha, an increase in population density of 100 people decreases average landholding size by 0.12 ha, which is fairly significant given that farms are very small in Malawi.

Second, higher population density initially leads to higher agricultural wage rates, but this trend reverses at a population density per square kilometer of 257, near the 70th percentile of the

Table 4
Factors affecting household well-being.

Covariates	(1) Off-farm income/AE		(2) Total household income/AE	
	Coeff.	p-Value	Coeff.	p-Value
Population density * 10[a]	601***	(0.00)	555***	(0.00)
Population density^2 * 10[a]	−0.99***	(0.00)	−0.08**	(0.02)
Real retail maize price	2902	(0.38)	2643	(0.48)
Fertilizer price	57	(0.97)	50	(0.98)
Agricultural wage rate	−2218**	(0.02)	−4814***	(0.00)
Household landholding	−946	(0.12)	680	(0.32)
Kilograms of subsidized improved maize seed acquired	−6	(0.89)	39	(0.41)
Kilograms of subsidized fertilizer acquired	0.50	(0.93)	17***	(0.01)
=1 if farm credit organization in village[a]	3877***	(0.00)	3265***	(0.00)
Distance to paved road[a]	−47***	(0.01)	−66***	(0.00)
Distance to main district market[a]	−2	(0.87)	−7	(0.64)
Real total value of household assets	0.003	(0.12)	0.006***	(0.00)
Age of household head in first survey year[a]	42	(0.73)	50	(0.72)
Age of household head in first survey year^2[a]	−1	(0.53)	−1	(0.62)
=1 if household head attended school[a]	1437	(0.11)	1960*	(0.06)
=1 if household headed by female	−5449***	(0.01)	−5812**	(0.01)
Household adult equivalent	−892**	(0.03)	−1833***	(0.00)
Death of household head or spouse, past 2 yrs	2745	(0.31)	3411	(0.26)
Net primary productivity[a]	0.29*	(0.07)	0.26	(0.15)
Elevation[a]	−3	(0.57)	−7	(0.32)
Elevation^2[a]	0.004	(0.21)	0.004	(0.30)
Cum. rainfall over current growing season, in cm	0.28	(0.90)	3	(0.29)
Population Density Turning Point	295	350		
I. Direct effect: APE of population density + pop Density^2 * 10	197***	(0.00)	220***	(0.00)
II. Indirect Effect: APE of population density through landholding, wages, and mz price * 10	13	(0.22)	−12	(0.35)
III. Total Effect: ATPE, direct + indirect * 10	210***	(0.00)	208***	(0.00)
Observations	4006		4006	
R^2	0.05		0.07	

Notes: APE = average partial effect, ATPE = Average total partial effect. p-Values in parentheses; model includes time averages of time-varying covariates, year dummies, district dummies, and a constant.
*** The corresponding coefficients are statistically significant at the 1% level.
** The corresponding coefficients are statistically significant at the 5% level.
* The corresponding coefficients are statistically significant at the 10% level.
[a] Time-constant factor that does not vary over time, and only changes spatially.

population density distribution in our sample. The concave relationship may indicate that wage rates get bid up at low levels of population density as labor is a relatively scarce resource. Once a certain level of population density is reached however, wage rates decline as labor becomes cheap relative to land. This finding is generally consistent with the both the Boserup (1965) and *induced innovation* hypotheses.

Third, population density is found to put some upward pressure on maize prices in Malawi. A 10 person increase in population density increases retail maize prices by 0.2% on average. This finding provides some evidence that there may be more demand for food in areas of high population density, and that maize may move from low density to high density areas with a mark-up for transport costs.

Fourth, evidence from this study suggests that increased population density has a small positive effect on fertilizer demand per hectare. This effect operates through *indirect* channels, like smaller landholding that is caused by increased population density. Input intensification seems to be going to maize production, as our results show a slight increase in maize yields from population density that also operates through *indirect* channels. We find that population density has no statistically significant effect on gross value of crop output per hectare, which could be due to lack of transport and perishability of higher value fruit and vegetables, along with lower prices for tobacco during the recent years of the study, which may have reduced farmers' incentives to plant it.

Fifth, we find that population density has a modest positive effect on total household income per capita, as a 10 person increase in population density raises per capita income by 220 Malawi kwacha (roughly US $1.39) on average. Most of this increase comes from gains off-farm, as the *direct* effects of population density such as market and institutional development may be providing some opportunities for people to work away from their own farm. However the descriptive analysis in this study indicates that much of the off-farm activities people engage in are relatively menial, such as piece-meal agricultural labor, petty trading, fishing, or selling charcoal, which offer few opportunities for livelihood improvement.

The overall picture that emerges from this study is that increases in population density are associated with reduced farm size, lower agricultural wage rates, and higher maize prices in Malawi. Any input intensification that occurs seems to be going to increasing maize yields, possibly in an attempt to improve household food security, as soils degrade and maize prices increase. Related to this, we find no evidence that increases in population density allow farmers to increase crop revenue per hectare. As a result, households in more densely populated areas increasingly rely on off-farm income to earn a living, but there appears to be a population density threshold beyond which households can no longer increase off-farm income per capita. Households who have relatively large landholdings, many assets, and have been to school appear to be able to increase intensification and well-being regardless of population density. Community-level characteristics and agronomic factors also play an important role in the ability of households to intensify production, and improve well-being. Households in areas with higher rainfall and higher elevation get higher maize yields, as do households that are closer to paved roads. The presence of a farm credit organization is associated with more fertilizer use per hectare, higher yields, off-farm income and total households income.

Findings from this study raise questions about the viability of smallholder agriculture in rural areas of high population density in Malawi. The fact that limited resource farmers in densely populated areas seem to be focusing resources on maize cultivation to ensure their own food security is unsustainable given population growth, shrinking farm sizes, and declining soil fertility. We find that the input subsidy program has made a small positive impact on fertilizer intensification, and maize production. However it has not increased gross value of crop output, and may have caused an expansion of maize production at the expense of other crops. Our results highlight the need for policies that facilitate credit access, improve transportation, and develop markets for high valued products, so that farmers in areas of high population density can increase farm income per hectare. However, there are people in areas of high rural population density who have such small landholdings that agriculture may not be a realistic possibility for earning a living. Therefore, policies that allow households to buy and sell land, facilitate migration and help develop the non-farm sector are crucial. Finally we find that households where the head has attended school have higher incomes than other households. This illustrates the need for government to invest in education so that future generations of Malawian can recognize new opportunities both inside and outside of agriculture.

Appendix A. Descriptive statistics for variables used in the analysis

	Mean	Median
Dependent variables		
Household landholding in Ha[a]	1.07	0.81
Real agricultural wage rate, in 2009 kwacha/day[a]	257	198
Real retail maize price (kwacha/kg) [a]	28	25
Total fertilizer use (kg/ha)	89	62
Maize yield (kg/ha)	808	576
Real gross value of crop output (kwacha/ha)	40,091	17,784
Real off-farm income (kwacha/AE)	6991	1943
Real total household income (kwacha/AE)	12,636	6884
Covariates		
Population density[b]	203	196
Population density squared[b]	53,845	38,818
Real commercial fertilizer price (kwacha/kg)	93	81
=1 if farm credit organization in village[b]	0.37	–
Distance to paved road, in km[b]	19	10
Distance to main district market, in km[b]	40	35
Real total value of household assets, in kwacha	50,657	12,550
Kilograms of subsidized fertilizer acquired	44.18	10
Kilograms of subsidized seed acquired	1.24	0
Age of household head in first survey year[b]	45	42
Age of household head in first survey year squared [b]	2319	1764
=1 if household head attended school[b]	0.73	–
=1 if household headed by female	0.27	–
Household adult equivalent	4.14	3.92
Death of household head or spouse, past 2 yrs	0.03	–
Net primary productivity (NPP) [b]	8823	7599
Elevation (meters above sea level) [b]	880	843
Elevation squared[b]	893,556	710,502
Cum. rainfall over current growing season in cm	960	978
Average of growing season rainfall, past 20 years in cm	9901	9638
CV past 20 year rainfall, in cm	0.21	0.21

Note: Real prices are in 2009 Malawi kwacha, US \$1.00 ≈ 150 Malawi kwacha during survey periods.
[a] Variable is a dependent variable in some equations and a covariate in others.
[b] Time-constant factor that does not vary over time, and only changes spatially.

References

Alwang, J., Siegel, P.B., 1999. Labor shortages on small landholdings in Malawi: implications for policy reforms. World Dev. 27 (8), 1461–1475.

Awudu, A., 2007. Spatial and Vertical Price Transmission in Food Staples Market Chains in Eastern and Southern Africa: What is the Evidence? Paper Prepared for the Conference on Staple Food Trade and Market Policy Options for Promoting Development in Eastern and Southern Africa, 1–2 March 2007, Rome, Italy.

Balk, D., Yetman, G., 2004. The Global Distribution of Population: Evaluating the Gains in Resolution Refinement. Working Paper. Center for International Earth Science Information Network (CIESIN), Columbia University.

Binswanger, H., McIntire, J., 1987. Behavioral and material determinants of production relations in land-abundant tropical agriculture. Econ. Dev. Cult. Change 36 (1), 73–99.

Boserup, E., 1965. The Conditions of Agricultural Growth: The Economics of Agrarian Change under Population Pressure. Allen & Unwin, London.

Bremner, J., 2012. Population and Food Security: Africa's Challenge. Population Reference Bureau, Policy Brief. <http://www.prb.org/pdf12/population-food-security-africa.pdf>.

Chibwana, C., Fisher, M., Shively, G., 2011. Land allocation effects of agricultural input subsidies in Malawi. World Dev. 40 (1), 124–133.

Chirwa, E., 2008. Land Tenure, Farm Investments and Food Production in Malawi. Institutions and Pro-Poor Growth (IPPG) Discussion Paper Series No. 18.

Climate Research Unit (CRU), University of East Anglia, 2011. CRU-TS 3.1 Climate Database. CRU Time Series (TS) High Resolution Gridded Datasets, NCAS British Atmospheric Data Centre. <http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276>.

Dorward, A., 2006. Markets and pro-poor agricultural growth: insights from livelihood and informal rural economy models in Malawi. Agric. Econ. 35, 157–169.

Dorward, A., Chirwa, E., 2011. The Malawi agricultural input subsidy programme: 2005–6 to 2008–9. Int. J. Agric. Sustain. 9 (1), 232–247.

Drechsel, P., Gyiele, L., Kunze, D., Olufunke, C., 2001. Population density, soil nutrient depletion, and economic growth in sub-Saharan Africa. Ecol. Econ. 38, 251–258.

FAOSTAT, 2012. Food and Agriculture Organization of the United Nations. <http://faostat3.fao.org/home/index.html>.

Goldewijk, K., Beusen, A., de Vos, M., van Drecht, G., 2011. The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years. Glob. Ecol. Biogeogr. 20 (1), 73–86.

Gondwe, D.O.C., 2002. Land Reform in Malawi. Presented at the Annual Meeting for FIG Commission 7 in Pretoria, South Africa, From 4th–8th November, 2002. <http://www.fig.net/commission7/pretoria_2002/papers/SYM_LR_PRETORIA_PAPER_GONDWE.pdf>.

Government of Malawi (GOM), 2002. Malawi National Land Policy. Ministry of Lands, Physical Planning, and Surveys, Lilongwe.

Haggblade, S., Hazell, P.B.R., Reardon, T., 2009. Transforming the Rural Nonfarm Economy. Issue Briefs 58. International Food Policy Research Institute (IFPRI), Washington, DC.

Hayami, Y., Ruttan, V., 1971. Agricultural Development: An International Perspective. Johns Hopkins Press, Baltimore.

Jayne, T.S., Mather, D., Mason, N., Ricker-Gilbert, J., 2013. "How do fertilizer subsidy programs affect total fertilizer use? A synthesis of the evidence on "crowding in/out" in sub-Saharan Africa. Agric. Econ. 44 (6), 687–703.

Kanyongolo, E., 2005. Land occupations in Malawi: challenging the neoliberal order. In: Moyo, S., Yeros, P. (Eds.), Reclaiming the Land: The Resurgence of Rural Movements in Africa, Asia and Latin America. Zed Books, London and New York.

Kishindo, P., 2004. Customary land tenure and the new land policy in Malawi. J. Contemp. Afr. Stud. 22 (2), 213–225.

Lunduka, R., Ricker-Gilbert, J., Fisher, M., 2013. What are the farm-level impacts of Malawi's Farm Input Subsidy Program? A critical review. Agric. Econ. 44 (6), 687–703.
Mapila, M.A.T.J., Kirsten, J.F., Meyer, F., Kankwamba, H., 2013. A Partial Equilibrium Model of the Malawi Maize Commodity Market. Discussion Paper #01254. International Food Policy Research Institute, Washington, DC.
Mason, N., Ricker-Gilbert, J., 2013. Disrupting demand for commercial seed: input subsidies in Malawi and Zambia. World Dev. 45, 75–91.
McMillan, M.S., Masters, W.A., Kazianga, H., 2011. Rural Demography, Public Services, and Land Rights in Africa: A Village-Level Analysis in Burkina Faso. NBER Working Paper Series.
Mitchell, T., Jones, P., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25, 693–712.
Mueller, V., Quisumbing, A., Lee, H.L., Dropplemann, K., forthcoming. Resettlement for food security's sake: insights from Malawi's land resettlement project. Land Econ.
Myers, R.J., Jayne, T.S., 2012. Multiple-regime spatial price transmission with an application to maize markets in Southern Africa. Am. J. Agric. Econ. 94, 174–188.
National Statistical Office (NSO), 2008. 2008 Population and Housing Census. NSO, Zomba.
National Statistical Office (NSO), 2011. Integrated Household Survey 2010/11. Household Socio-Economic Characteristics Report. NSO, Zomba.
Pender, J., 1998. Population growth, agricultural intensification, induced innovation and natural resource sustainability: an application of neoclassical growth theory. Agric. Econ. 19, 99–112.
Pender, J., Place, F., Ehui, S., 2006. Strategies for Sustainable Land Management in the East African Highlands. International Food Policy Research Institute, Washington, DC.
Pingali, P.L., Binswanger, H., 1988. Population density and farming systems – the changing locus of innovations and technical change. In: Lee, R. (Ed.), Population, Food and Rural Development. Clarendon Press, Oxford.
Potts, D., 2006. Natural resource access in Southern Africa: the influence of political change and development practice. In: Tornimbeni, C., Zamponi, M. (Eds.), Comparing Rights: Land and Natural Resources in Africa. Bologna, Italy.
Rashid, S., 2004. Spatial Integration of Maize Markets in Post-Liberalized Uganda. Markets, Trade, and Institutions Division Discussion Paper No. 71. International Food Policy Research Institute, Washington, DC.
Ricker-Gilbert, J., Jayne, T.S., Chirwa, E., 2011. Subsidies and crowding out: a double-hurdle model of fertilizer demand in Malawi. Am. J. Agric. Econ. 93, 26–42.
Rodriguez, E., Morris, C.S., Belz, J.E., Chapin, E.C., Martin, J.M., Daffer, W., Hensley, S., 2005. An Assessment of the SRTM Topographic Products. Technical Report JPL D-31639. Jet Propulsion Laboratory, Pasadena, California, p. 143.
United Nations, 2011. World Population Prospects: The 2010 Revision. New York, New York, USA.
Van Campenhout, B., 2008. Modelling trends in food market integration: method and an application to Tanzanian maize markets. Food Policy 32, 112–127.
Woodhouse, P., 2006. Legitimizing markets or legalizing custom? Land commoditization and tenure reform in Africa. In: Tornimbeni, C., Zamponi, M. (Eds.), Comparing Rights: Land and Natural Resources in Africa. Bologna, Italy.
World Health Organization, 1985. World Health Organization Technical Report, Series No. 724, Geneva, Switzerland.
Wooldridge, J.M., 2010. Econometric Analysis of Cross Section and Panel Data, second ed. MIT Press, Cambridge, MA.
World Bank, 2013. Population Growth Rates (Annual%). <http://data.worldbank.org/indicator/SP.POP.GROW/countries?display=default> (accessed 11.09.13).
Zhao, M., Heinsch, F.A., Nemani, R.R., Running, S.W., 2005. Improvements of the MODIS terrestrial gross and net primary production global data set. Remote Sens. Environ. 95, 164–176.