Boserup versus Malthus: does population pressure drive agricultural intensification? Evidence from Burundi

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Abstract

Will a growing population lead to depletion of natural resources and eventually economic collapse, as predicted by Malthus, or rather to innovations in the agricultural sector improving agricultural potential of land, as hypothesized by Boserup? This centuries-old puzzle is as relevant as ever in some densely populated regions of Sub-Saharan Africa where population growth is still alarmingly high and shows no sign of slowing down, leading to enormous pressure on land. In this paper, we quantify the relationship between population pressure and land intensification in Burundi, one of the most densely populated regions in Africa. Using data from a nationally representative agricultural survey (n=2050), we find evidence of both Malthusian and Boserupian processes. In line with Boserup's theory, the use of fertilizer and labour, yields and food production initially increases with population pressure, but decreases again when population densities exceed a critical threshold, supporting Malthus' prediction. For instance, in regions with a population density of less than 200 persons/km², every increase of 100 persons/km² leads to increases in yields of more than 20% but yields decrease as soon as a critical threshold of 500 persons/km² is reached. These limits to intensification confirm findings from previous studies on densely populated regions in Sub-Saharan Africa (Jayne, Chamberlin, & Headey, 2014).

Keywords: population density, land intensification, Boserup, Malthus, Burundi

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1. Introduction

Many regions in Sub-Saharan Africa have experienced a substantial increase in rural population densities in the last decade. Yet, few regions can increase food production through expanding arable land (Chamberlin, Jayne, & Headey, 2014) and farmers have no other options than to intensify production. This brings a recurrent debate, inspired by Malthus and Boserup, back to the forefront: can smallholder farmers, through innovation and intensification, manage to sufficiently increase land and labour productivity to feed a growing population, or will a vicious circle of degrading natural resources, declining landholdings per capita and stagnating yields be set in motion, leading to a Malthusian catastrophe?

A recent special issue of *Food Policy,* entitled *'Boserup and beyond: mounting land pressures and development strategies in Africa'* provided ample empirical evidence that both Malthusian and Boserupian processes co-exist. Several papers, based on different case studies, show that land productivity tends to increase up to a population density that is in the range of 450 to 600 persons/km² - after which it gradually declines (Jayne et al., 2014). Moreover, it seems that population pressure substantially increases fertilizer use, but has a much smaller impact on yields and that it is negatively associated with total farm income due to smaller landholdings per capita (Headey, Dereje, & Taffesse, 2014; Jayne et al., 2014; Josephson, Ricker-Gilbert, & Florax, 2014; Muyanga & Jayne, 2014; Ricker-Gilbert, Jumbe, & Chamberlin, 2014). In addition, the increase in yields can partially be attributed to unsustainable depletion of soil fertility (Drechsel, Gyiele, Kunze, & Cofie, 2001). Thus we can conclude that population growth does drive intensification - as predicted by Boserup, but only up to a certain point, when it seems to bounce against limits of the production environment. These ceilings to substantial and sustainable increases in food production, combined with population growth increase the danger of a Malthusian catastrophe.

The objective of this study is to add empirical evidence to this debate. The novelty of this paper lies in the analysis of unique data from Burundi, arguably one of the most interesting countries for an investigation into the merits of Boserup's and Malthus's hypotheses. Burundi is distinct in many respects from other Sub-Saharan African countries because of its high population densities, the exhaustion of arable land, the key role of subsistence agriculture in society and its geographical remoteness from world markets. Burundi's average population density is extremely high, close to 400 persons/km², which is significantly greater than most other African countries. Population growth is estimated at 3% and more than 90% of the population lives in rural areas. As a result more than 5% of the households in our sample live in regions with a population density in excess of 600 persons/km². With the exception of a study in Kenya where 10% of the households lived in regions with a population density of more than 700 persons/km² (Muyanga & Jayne, 2014), the maximum population density in previous studies is around 600 persons/km². The civil war in Burundi and neighbouring Rwanda has often been cited as a classic example of a Malthusian crisis, partially caused by competition for land (André & Platteau, 1998). It has been shown that the violence was more severe in the most densely populated regions of the country (Bundervoet, 2009; Verpoorten, 2012). Even today, land conflicts between - and within - households are still widespread, causing social tensions (van Leeuwen, 2010). Relieving pressure on land through land intensification can thus help avoid new conflicts from emerging. In addition the government is – barring the coffee sector – relatively uninvolved in the agricultural sector. Agricultural research and extension services are limited and there are no large-scale fertilizer subsidy schemes or micro-credit programmes (Baghdadli, Harborne, & Rajadel, 2008; Republic of Burundi, 2011). Finally, Burundi is - to a large extent - isolated from world markets because it is landlocked and the interregional infrastructure is poor. This makes it very expensive to import fertilizers and also limits access to external knowledge about best practices for land intensification (Baghdadli et al., 2008). As a result, if land intensification does occur, it will primarily be the result of farmers' efforts using locally availably inputs and knowledge to increase food production.

Given these adverse local conditions, we investigated whether farmers are nevertheless able to intensify production in response to intense population pressure. More particularly, we examined the association between population pressure and (i) land holdings (ii) land intensification and diversification out of agriculture, and (iii) yields, food production and incomes. We attempt to disentangle the direct and indirect influences that population densities have on yields, production and incomes. To this end, we draw on a unique cross-sectional dataset from an agricultural survey conducted in Burundi in 2010-2011 and combine this rich dataset with information on population density at communal level derived from a national census conducted in 2008.

Our results reveal that both Malthusian and Boserupian processes co-exist in Burundi. Land intensification occurs with population pressure, but yields stabilize at around 500 persons/km², while household level food production decreases because of smaller landholdings. This is accompanied by increases in off and non-farm income, but these additional sources of income are insufficient to reverse the trend of declining incomes associated with increased pressure on the land. Agricultural and broader socio-economic policies will be required to halt this trend.

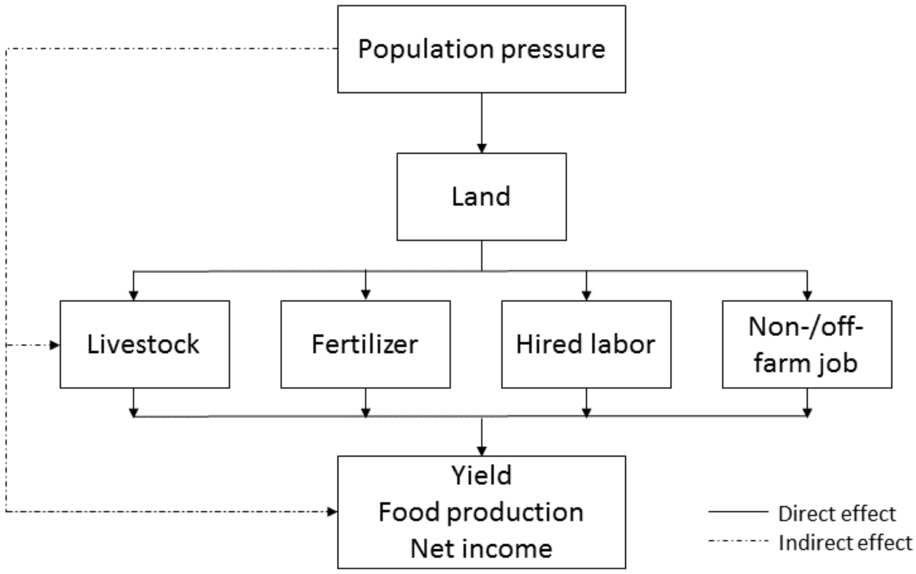
The remainder of the paper is structured as follows. In the next section, we outline our methodology and briefly discuss various robustness checks that we carried out. We describe our data and discuss its strengths and weaknesses and then present our results. In the conclusions, we compare our findings with those in the literature.

2. Methodology

Framework

We hypothesize that population pressure affects several key elements of rural livelihoods in Burundi through direct and indirect pathways, which are depicted in figure 1.

Figure 1: Conceptual framework



Population pressure *directly* influences landholdings, inputs and finally well-being as expressed in yields, food production and household incomes. Population pressure also has an *indirect* effect on these variables. For instance, if average landholdings decrease because of population pressure and if land size is an important determinant of income, population pressure *indirectly* influences income through the pressure it exerts on land availability. Distinguishing direct from indirect pathways allows us to identify the key processes that drive agricultural intensification. More formally, we estimate the following set of equations:

$$\begin{cases} \log(L_{ij}) = \alpha_L D_j + \sigma_L X_i & (1) \\ \mathrm{Input_{ijk}} = \alpha_k D_j + \alpha_{k^2} D_j^2 + \rho_k L_i + \sigma_k X_i \quad {\scriptstyle (k=1\rightarrow 4)} & (2) \\ \log(y_{ijh}) = \alpha_h D_j + \alpha_{h^2} D_j^2 + \rho_h L_i + \sum_k \beta_{kh} Input_k + \sigma_{yh} X_i \quad {\scriptstyle (h=1\rightarrow 3)} & (3) \end{cases}$$

The variables on the left hand side are respectively landholdings, L, a vector of four inputs (livestock, fertilizer, hired labour, and off/non-farm employment) and a vector of three outcome variables, y (yield, food production and household income). The household and the commune are identified by i, j, respectively; D_j represents population density for commune j and X_i represents a set of household and farm characteristics.

It is important to note that the set of equations is recursive. A household's landholding (eq. 1) influences the inputs used (eq. 2), while the final outcomes (yield, production and income) (eq. 3) are a function of both landholdings (eq. 1) and the inputs used by the household (eq. 2). As a result, population density has both a direct effect on the outcomes, as well as an indirect effect through eq. 1 and eq. 2. Taking the total derivative of the outcome variables with respect to population density allows us to calculate total effect of population densities on yields, food production and total incomes. In addition, the relative importance of the direct and indirect pathways can be obtained. Formally, the total derivative equals:

$$\frac{\boldsymbol{d}\log(y_{ijh})}{\boldsymbol{d}D_j} = \underbrace{\alpha_h + 2\alpha_{h^2} D_j}_{\text{Direct effect}} + \underbrace{\rho_1 \frac{\partial L_{ij}}{\partial D_j} + \sum_{k=1}^{4} \beta_{kh} \frac{\boldsymbol{d}Inputs_{ijk}}{\boldsymbol{d}D_j}}_{\text{Indirect effect}} \tag{4}$$

This total derivative can be interpreted as a semi-elasticity. It clearly shows the direct effect of population density on the outcomes and the indirect effect through land and through the four inputs. Those inputs are, in turn, directly and indirectly influenced by population densities[1].

In equations 2 and 3 we include the squared term of population density to allow for non-linear effects. As discussed in the introduction, previous studies have found land intensification up to a certain critical level of population density after which land intensification decreases again. To identify this threshold it is necessary to include the square of population density in the regressions. This also implies that the total effect of population density on the outputs (eq. 4) is not constant with increasing population density. As a result, in the results section, the semi-elasticities are reported for successive quartiles of population densities. Previous studies have not identified a threshold for landholdings, which generally decline continuously in size with population density. Therefore, population density squared is not included in the first equation.

Inputs (eq. 2) are broadly defined and also include the livelihood strategies adopted by households to survive in densely populated regions. Thus, inputs do not only include livestock, fertilizer and labour, but also diversification out of agriculture. The latter strategy is important to consider, because off-farm and non-farm jobs can be important in more densely populated regions (Jayne et al., 2003). Moreover, some previous studies have found that households with a larger income from non-farm sources also achieve higher land productivity, as the additional revenue is partially invested in agriculture (Ellis & Bahiigwa, 2003). Livestock was also considered as an input, because manure is an important organic fertilizer in Burundi (Cochet, 2004). However, in contrast to fertilizer and hired

[1] Formally: $\frac{\boldsymbol{d}Inputs_{ijk}}{\boldsymbol{d}D_j} = \frac{\partial Input_{ijk}}{\partial D_j} + \frac{\partial Input_{ijk}}{\partial L_j}\frac{\partial L_{ij}}{\partial D_j}$, showing the direct and indirect effect of population density on inputs.

labour, it can also be seen as an output because of its nutritional value and its importance as a store of wealth.

The set of household characteristics include the age of the household head and age squared - to take into account lifecycle effects, the number of adult sons, the size of the household, the educational level of the household head and whether or not the household is female-headed. In addition, access to markets, measured in terms of the distance to the capital and an accessibility index for the nearest village[2], and two environmental conditions (elevation above sea level, provincial rainfall) are also included.

Estimation strategy

The set of three equations (eq. 1, 2 and 3) were estimated separately. This provides unbiased estimates and standard errors given that the set of equations is recursive (Greene, 2003).

Equation 1 was estimated with OLS. Estimating equation 2 posed a practical challenge. Ideally, all inputs should be considered as continuous variables, because the amount of fertilizer/hired labour applied determine yields and farm income. However, only 39% of the households in the sample had applied fertilizer in the past year and only 57% had hired labour. Similarly, many households were not active in the labour market and did not, therefore, have any non-farm income to report. Only livestock could be treated as a continuous variable because 76% of the households had livestock. Hence, except for livestock, the inputs were considered as dichotomous variables and were estimated with probit models. An additional advantage of probit models is that they reduce the chances of measurement error in the data. For instance, it is unlikely that households wrongly reported whether they used fertilizer or hired labour, while the exact cost or levels of use of these inputs are susceptible to measurement error. Tobit models are another option for estimating these equations[3]. Tobit models assume that a zero value is an outcome of a rational choice that takes the truncated nature of the data into account and provides unbiased estimates, while still allowing the researcher to take into account the continuous structure of the data. The model was re-estimated with Tobit models and results were very similar to the base models (available upon request).

Finally, equation 3 was estimated with Seemingly Unrelated Regression (SUR). This improved the efficiency of the estimation because errors in the equations for yields, food production and income are likely to be correlated with each other. Because of concerns about measurement error of these

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[2] This accessibility index equals the sum of the four binary variables: there is a road that crosses the village, the nearest provincial road is less than 5km from the village, the nearest paved road is less than 5km from the village, and the nearest market is less than 5km from the village.

[3] Heckman models are a third viable option. However, these require an exclusion restriction, i.e. a variable that explains a zero outcome, but does not appear in the equation itself. We could not identify such a variable in our dataset.

outcome variables, these equations were also re-estimated with robust regressions (Verardi & Croux, 2008). Again, results were very similar and are available upon request.

The endogeneity of population densities is a concern in all our estimations. For instance, regions with a higher agro-ecological potential may have a higher population density and higher yields. Omitting the variables for soil fertility could thus introduce reversed causality. In this view, the endogeneity of population density might have the greatest influence on outcome variables (eq. 3), less influence on inputs (eq. 2) but can be considered not to influence the distribution of land (eq. 1). To partially mitigate these concerns about endogeneity, we included regional fixed effects in our estimations. Burundi has 11 different natural regions with different agricultural potential ranging from lowland to mountains. Using these as variables we were able to capture how variations in population pressure within a region influence agricultural intensification. In addition, two proxies for soil fertility were also included in the regressions: the share of marsh land and the share of land that is double cropped. Marshlands are low lying areas that retain water and these areas are often used to cultivated rice. Land that is double cropped , i.e. cultivated during several successive seasons, is likely to be more fertile than land that is only cultivated during one season and then left fallow to regenerate. We will provide empirical evidence that double-cropping is not more common in densely populated regions and is more an indicator of soil fertility rather than a strategy to increase food production in densely populated regions. Unobserved household characteristics are another concern since we cannot control for these directly - as we do not have a panel dataset. For instance, households with higher yields and income may invest their surpluses in additional inputs such as livestock or fertilizers. To test the importance of this effect, we aggregated the data at communal level and re-estimated the equations. After doing so, our analysis covered 124 communes. The results are reported in the appendix and confirm the findings at household level.

Although, our results are robust to several different specifications, the findings should carefully be interpreted, and as showing associations – and not causations – between population density and the outcomes of interest. These associations are nonetheless interesting because a positive association between population density and yields – be it because of population-induced intensification or because population grows faster in fertile region - would reduce the likelihood of a Malthusian crisis.

Data

We used data from a national representative agricultural survey of 2560 households conducted in 2011/2012 by the Statistical Office of Burundi and the Ministry of Agriculture, which was financially supported by the Belgian Technical Cooperation and the World Bank. This was the first nationally representative agricultural survey in Burundi since the 1970s and its main purpose was to update agricultural statistics and to provide reliable production figures at the provincial level.

A two-stage stratified design was adopted to randomly select households. First, 20 sectors[4] were randomly selected within each of the 16 rural provinces[5]. Within each sector, all the households were enumerated and 8 households were randomly selected to participate in the survey. Details of the sampling procedure can be found in a government report on this agricultural survey (Republic of Burundi, 2013). These households were interviewed several times during the three seasons by trained enumerators.

The survey contained 14 sections with questions related to agricultural production and the socio-economic status of the household. Each of the fields used by the households was precisely measured with GPS. Details of the total annual production of all main food crops were collected. In Burundi's mixed-cropping system it is difficult to obtain details of yields of individual crops or to identify how much land has been devoted to each particular crop. We therefore estimated average yields as the sum of total annual production of all food crops, weighted by its calorific content, and divided by total landholdings. This number was then divided by the calorific content of beans, one of the main staple crops in Burundi, to make it more tangible. Yields are thus expressed in kg/ha. Food production is defined as total on-farm production expressed in its calorific content per adult equivalents[6] per day, a proxy for food availability within the household. To obtain total income, we expressed the purchasing power of off-/non-farm income in terms of calories per day and adult equivalent, subtracted the cost of fertilizers and hired labour and added food production[7]. The calorific content of food crops[8] was chosen instead of prices, as most food production is for subsistence purposes and only surpluses are sold on the market. In addition, the survey did not collect prices at farm or village level and we only had access to average prices for Burundi, which did not reflect regional differences. However, the correlation between calorific content and these prices was 85%. Hence, our choice of the weights is unlikely to affect the main results.

The survey excluded cash crops. In some provinces, cash crops, especially coffee, contribute significantly to total farm income. However, coffee is generally considered to be less profitable than food crops and is mainly still cultivated for historical reasons (Baghdadli et al., 2008; Oketch & Polzer, 2002; Republic of Burundi, 2014). We are therefore fairly confident that including coffee in the estimation of average yields would not have increased yields substantially. While farm incomes and

[4] The sectors, known as Zones Dénombrements (ZD), represent relatively small administrative units that include several villages. ZDs in predominately urban areas were excluded from the survey.
[5] The province of Bujumbura Mairie was excluded because it is dominated by the capital Bujumbura and can be considered an urban region.
[6] We followed the suggestion of FAO (2005) and defined adult equivalents as: $AE = (Adults + 0.3 * Children)^{0.9}$
[7] Using national price data for staple foods in Burundi, we estimated the price of 1000 calories as 310 FBU ($ 0.21) (Republic of Burundi, 2013)
[8] The calorific contents of crops were taken from FAOSTAT .

total income will be underestimated in regions where coffee or tea is cultivated, this effect should be partially picked up by the regional fixed effects that have been included in all estimations.

Before conducting the analyses, the dataset was thoroughly cleaned to ensure the reliability of our results. Besides removing observations with missing variables, we excluded 48 farms with landholdings above 20ha, because these farms are not representative of Burundi. Yields are especially sensitive to measurement error. Therefore, we discarded the households with the 5% highest and lowest yields. In the end, 2050 observations remained in our dataset.

We complemented this dataset with secondary sources about population density and rainfall. A national population census was conducted in 2008 by the Government of Burundi, which enabled us to calculate population density at the communal level (République du Burundi, 2010). Rainfall data were collected by IGEBU, the Geographical Institute of Burundi, which collects rainfall data but only at the provincial level, as Burundi has only a few weather stations.

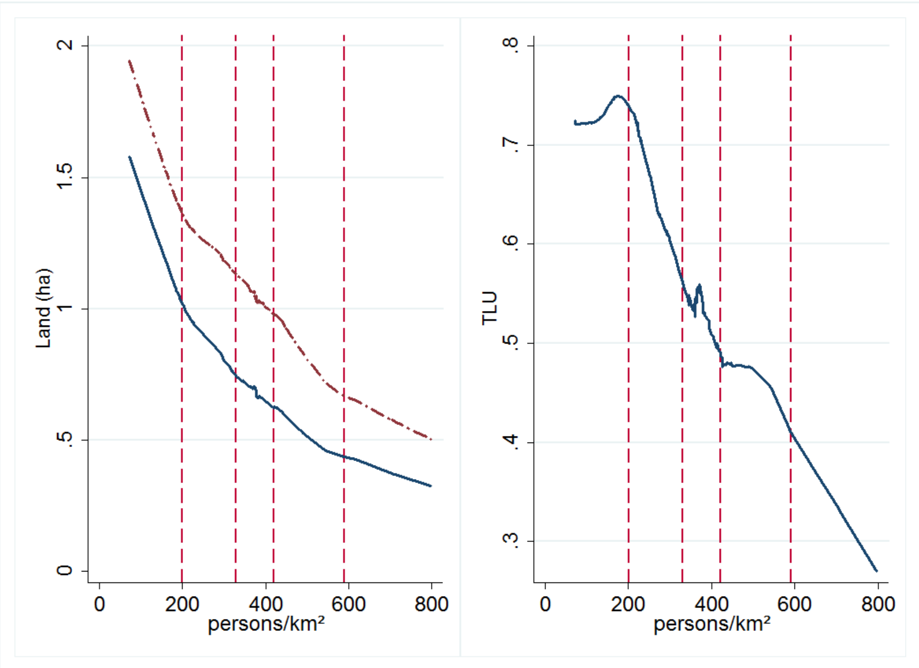
3. Results

Descriptive results

In this section we show the association between population density and landholdings, land intensification, diversification out of agriculture, food production per hectare and per adult equivalent and net-income with non-parametric regressions (figures 2 to 5). In all these figures the x-axis represents rural population density (persons/km²) and the y-axis shows the selected variable. The vertical dashed lines indicate the four different quartiles (at 200 persons/km², 330 persons/km², 421 persons/km²) and the 95th percentile (590 persons/km²) of the distribution of population density.

Landholding sizes and cultivated land area gradually decline with increasing population pressure (figure 2, left panel). Average landholdings are greater than 1ha in regions with a population density of less than 200 persons/km², but are smaller than 0.5ha in regions with a population density of more than 450 persons/km². Additional analyses showed that households cultivate on average 6 plots and this figure does not decrease with increasing population density. Thus, the plots are much smaller in densely populated regions, implying that land fragmentation is even more pronounced in these regions. This is probably caused by the customary practice of sharing the best plots of land equally among all male heirs. Land in the marshes is especially valuable and is therefore not passed to just one heir, but is equally shared among all the adult sons. We found that the share of households with access to land in the marshes remains constant at roughly 40% with increasing population pressure, with the average plot size decreasing . Cultivated land area was defined as the total land area that was cultivated during the agricultural year. Although annual crops such as banana are important in Burundi, double-cropping, i.e. cultivating the same field during several successive seasons, is a common practice in many fields (Cochet, 2004). Therefore, the total cultivated area is always substantially greater than total landholdings (figure 2, left panel, dashed line). The ratio of total cultivated land area to landholdings seems to remain stable with increasing population pressure. This indicates that land intensification does not occur through a shortening of fallow periods or increasing double cropping, perhaps because double-cropping is already a widespread practice in Burundi. This finding is important because the share of double cropped land and the share of marshland in total landholdings will be included as independent variables in the econometric analyses. As already argued, these variables partially control for soil characteristics. If they were correlated with population pressure, they should have been included as 'inputs' (eq. 2) in our empirical framework and could not be considered to be appropriate proxies for soil fertility. Erosion management is not very common, with only 26% of the fields protected by any form of soil protection and only 3% of the fields terraced (Republic of Burundi, 2013). We could not detect any association between population pressure and soil protection.

Figure 2: Total landholdings/cultivated land area and livestock as a function of population density



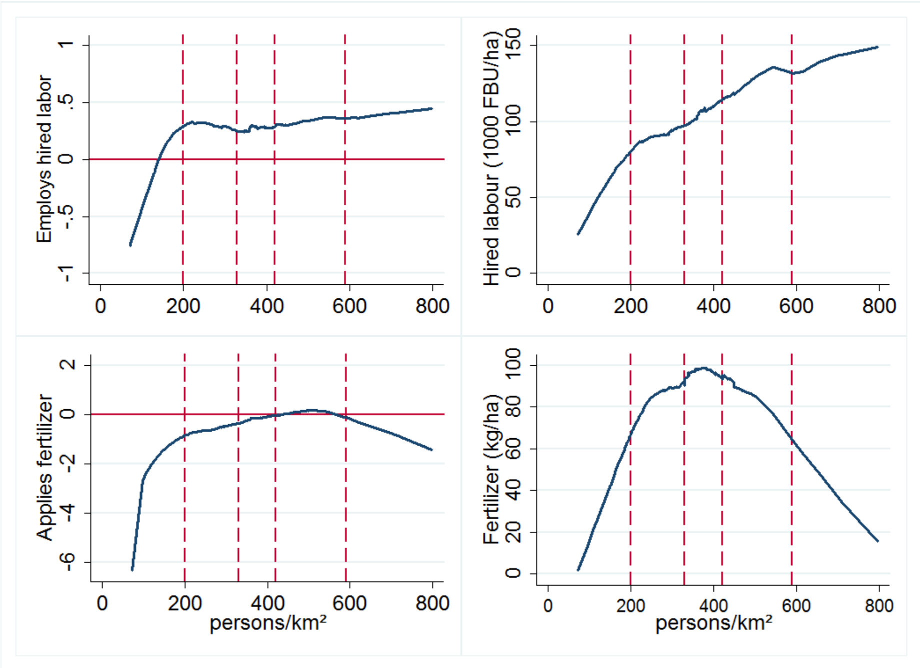
Livestock expressed in Tropical Livestock Units (TLU): cattle=0.7; pig=0.2; sheep, goat=0.1; poultry=0.01

We now turn our discussion to the relation between population pressure and the use of inputs. Livestock numbers decrease steeply with increasing population pressure (figure 2, right panel). This is in line with qualitative work that related the decrease in livestock to the loss of grazing land in densely populated regions (Hatungumukama, Hornick, & Detilleux, 2007). Analyzing this relationship in more detail revealed that the probability of keeping cattle was 20% in the first quartile of the distribution of population density, but decreases to less than 5% at the 95th percentile. The probability of keeping sheep, goats and poultry increases with pressure on land. Hence, households in densely populated regions shift to smaller animals, which are less vulnerable to shocks and poor quality feed. We examined the probability of applying fertilizer and labour and, when they are used, the actual amount applied per ha. The probability of hiring labour increases with population density up to 200 persons/km² and remains constant thereafter (figure 3, top left). In these regions, more than 50% of the households engaged wage labourers. Moreover, the cost of wage labourers also increases steadily with rising population pressure (figure 3, top right). Hence, there is evidence of land intensification through more intense, manual cultivation when population pressure mounts. It should be noted that we may underestimate this association between population density and labour intensity. The survey did not capture information on the salaries paid to wage labourers, but only measured how much was spent on hiring additional labour per field and season. If wages are lower in the most densely populated regions (as predicted by Boserup), the number of employed labourers in these regions will be underestimated relative to more sparsely populated regions, where wages are higher. This would reduce the strength of the association between population density and the demand for wage labourers.

Fertilizer use increases with population density up to 500 persons/km² and decreases thereafter (figure 3, bottom left). Nonetheless, even at its peak, only slightly more than 50% of the households apply fertilizers. Access to fertilizers for smallholders is problematic in Burundi. A similar relationship is found when examining the association between the amount of fertilizer per hectare and population pressure. The amount of applied fertilizer first increases from a very low level to around 100 kg/ha in areas with a population density of between 300 and 450 persons/km² and then decreases again (figure 3, bottom right). Cochet (2004) argued that banana is an important organic fertilizer in Burundi and observed a shift from the use of manure to banana mulch as population pressure increases. In our sample, the number of household cultivating banana increased from 72% in the first quartile of the distribution of population density to 82% in the fourth quartile (results not shown). However, the share of land devoted to banana cropping seems to be uncorrelated with population density and varied between 30% and 36%. The share of land covered with bananas was therefore not included as an input in our econometric model.

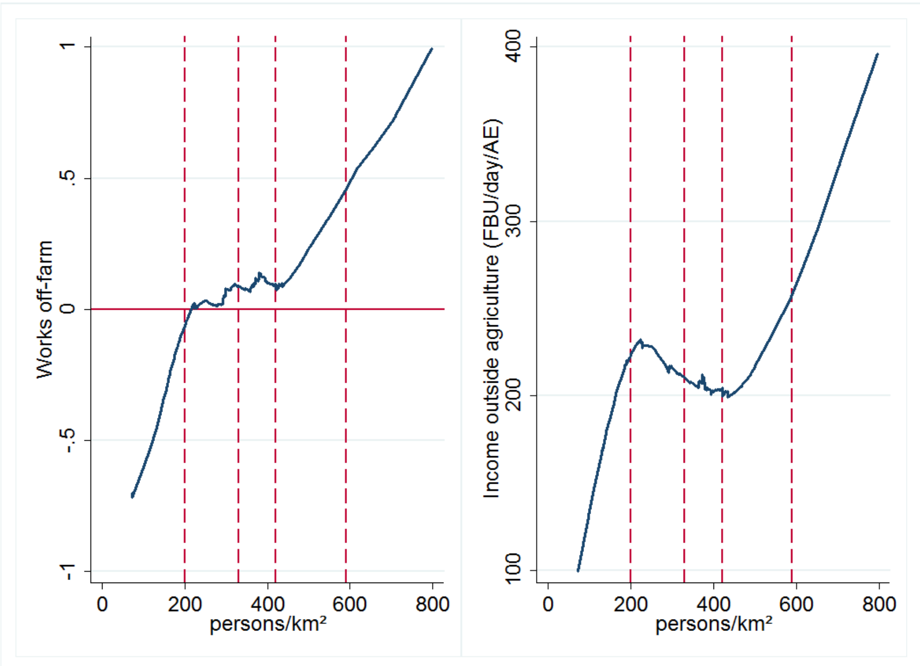
Diversification out of agriculture is often considered an important livelihood strategy for land constrained households. Households in densely populated regions are far more likely to have at least one member engaged in off- or non-farm work (figure 4, left). Income per adult equivalent also increases with population density. Income from off- or non-farm work is around 200 FBU ($ 0.13) per day and adult equivalent in regions with a population density between 200 and 400 persons/km², and then further increases (figure 4, right).

Figure 3: Use of labour and fertilizer as a function of population density



The left panels shows the probability (in log odds) of hiring labour/applying fertilizer during the previous year on at least one plot. The horizontal line corresponds to a probability of 50%. The right panels show the use of labour and fertilizer per hectare among households that did use these inputs.

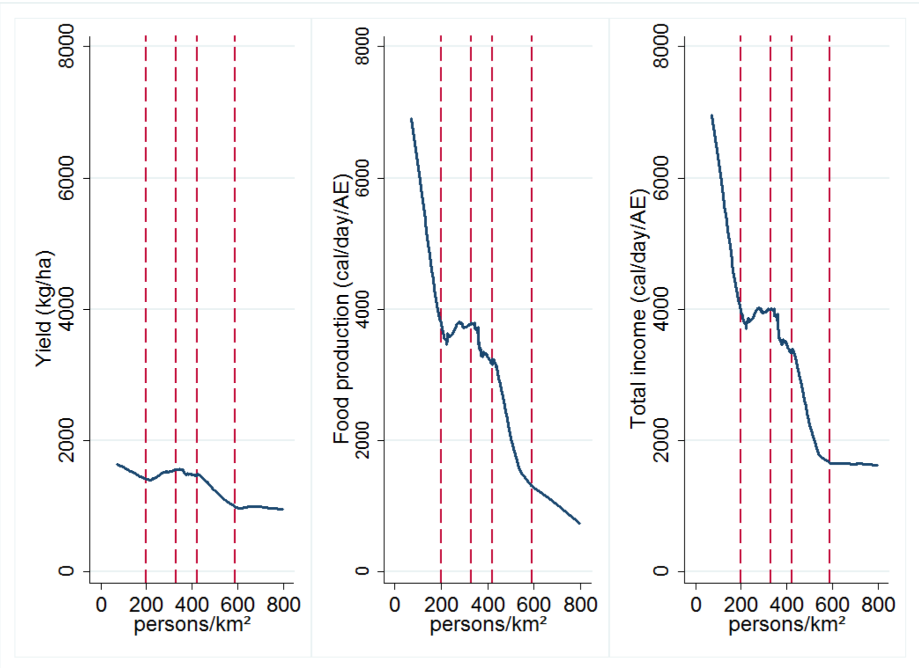
Figure 4: Non- and off-farm income as a function of population density



The left panel shows the probability in log odds of being engaged in off-farm work. The horizontal line corresponds to a probability of 50%. The right panel shows total income derived from off-farm and non-farm jobs - only considering households that are active on the labour market.

Finally, we examined the relation between population pressure and yields, food production and income. Figure 5 shows that, up to 450 persons/km², yields vary between 1400 kg/ha and 1600 kg/ha and then decrease rather steeply to 1000 kg/ha. Food production and total income decrease continuously with increasing population density (figure 5, middle and right). This negative association is weaker for total income than for food production, especially in the last quartile of population density, because many households in densely populated regions complement income from food production with income from off-farm and non-farm employment. However, it seems that additional income from non-farm sources is insufficient to reverse or even halt the negative association between income and population pressure.

Figure 5: Yields, food production and farm income as a function of population density



The overall picture can be summarized as follows: higher population densities are associated with smaller landholdings and increased land intensification (through a higher demand for labour and fertilizer) as well as with a decrease in livestock (and thus the availability of manure). In general, food production per hectare and per adult equivalent is lower in densely populated regions, and off-farm and non-farm activities make a larger contribution to total income in these areas, suggesting a diversification out of agriculture. While these descriptive results confirm a scenario in which Malthusian and Boserupian forces co-exist, a more thorough econometric analysis can be used to shed light on the direct and indirect pathways through which population density affects agriculture.

Econometric results

In this section, we report the econometric analyses and quantify the direct and indirect pathways through which population pressure affects the agricultural system in Burundi. The direct and indirect effects for successive quartiles of population density on the variables of interest are reported in table 4.

The first regression explains landholdings (table 1) as a function of population density and household characteristics. We find a highly significant negative association between landholdings and population density: an increase of 100 persons/km² is associated with a 10% decrease in landholdings. Several household characteristics also correlate significantly with landholdings: they increase with the age of the household head, suggesting that wealth - in the form of land - is accumulated during a lifecycle. The strong correlation between adult sons and landholdings suggests that adult sons who leave the household to start their own family inherit on average 17% of the parental landholdings. The share of land in the marshes and the share of land that is double cropped is negatively correlated with landholding size. If these variables are indeed correlated with soil quality, as argued before, this indicates that households with better soils have less land. This is reasonable as households are likely to face a trade-off between inheriting or buying a lot of land of poor quality or less land with more fertile sols. Landholdings are also larger in more remote locations, i.e. further from the capital or close to less accessible villages.

Table 1: Landholding size decreases with population pressure

	Landholdings OLS
Population pressure: direct effect	
Population density (100 persons/km²)	-0.096***
Farm and household characteristics	
Age household head	0.0250***
Age²	-0.000134*
Female headed household	-0.0920*
Household size	0.0816***
Adult sons	0.165***
Education household head (0-2)	0.101***
Share land in marshes	-0.701***
Share land double cropped	-0.930***
Regional characteristics	
Distance to capital (km)	0.00596***
Accessibility of nearest village (0-5)	-0.0367**
Provincial rainfall (mm³)	-0.000182**
Elevation above sea level (m)	-0.000247*
R^2	30%

***,**,* significant at 0.01, 0.05,0.10 levels, respectively; Regional dummies included, but not reported; n=2050

Table 2 shows that livestock keeping, use of fertilizer and labour and diversification out of agriculture are all significantly correlated with population pressure. The correlation between livestock and population density is linear, but rather weak (table 2, column 1). An increase of population pressure of 100 persons/km² corresponds to a decrease of just 2.8% in livestock units. However, the positive association between landholdings and livestock is much stronger. If landholdings increase by 1ha livestock units increase by 10%. Thus, in densely populated regions, where average landholdings are small, there is less livestock. Hence, the direct and indirect pathways reinforce each other. The total effect of population pressure on livestock shows that an increase in population density of 100 persons/km² reduces livestock units by an average 3.5%.

The association between population pressure and fertilizer use is non-linear. All else remaining equal, the probability of using fertilizer increases up to 463 persons/km² and decreases thereafter (table 2, column 2). In addition, households with more land are more likely to use fertilizers. This is a paradox because it implies that the poorest households, i.e. those with little land, who are unlikely to be able to cover their subsistence needs, do not intensify production as much as wealthier households. Consequently, the direct and indirect effects (through landholdings) of population pressure on fertilizer use oppose each other. An increase of population density of 100 persons/km² increases the probability of using fertilizers by 16% in the first quartile of the distribution of population density, but the same increase in population density in the fourth quartile only increases the probability by 5%. This does not mean that there is less demand for fertilizer in densely populated region, even on the contrary, but just that continued population growth in the most densely populated regions is not associated with an increased demand for fertilizers. It may be that all the households in these regions who are sufficiently wealthy and have access to fertilizers, already use them, while in less densely populated regions there are still households who will invest in fertilizer if the pressure on the land further increases. Other important predictors of fertilizer use are the education of the household head, the share of land that is double cropped and the distance to the capital. The latter correlation is especially strong. For instance, there is a 78% probability that an average household 20km from the capital will use fertilizers and this probability falls to 57% at 60km from the capital.

There is a direct positive association between population pressure and the use of wage labour, but the magnitude of the effect is small and only significant at the 8% level. Landholding size is also positively correlated with hiring additional labour, weakening the total positive effect of population pressure on the demand for labour. Taking into account both direct and indirect effects, an increase of population density of 100 persons/km² increases the probability of hiring additional labour by an average 2 percent points. However, the effect differs with the initial levels of population density: it is positive in the first quartile (by 4 percent points), but almost zero in the fourth quartile. Some other covariates also correlate with demand for labour. The positive correlation between household size and hiring labour contradicts expectations, as larger households – presumably having more family labour – were expected to hire less labour.

We found a positive, but weak, association between population density and being active in the labour market. Remarkably, we did not find evidence of a negative correlation between landholding size and the likelihood of having a non-/ or off-farm job. This is a second paradox with regards to the poorest households, as we would have expected that these households would be the most active in the labour market as they are more likely to need non-farm income to survive. Perhaps, non-farm and off-farm jobs are limited and only available to (politically) well-connected households, independent of their socio-economic status (Vervisch, Vlassenroot, & Braeckman, 2013). Some other household characteristics are also associated with labour market participation: larger and male headed households are more likely to have members working off the farm, as well as households with a younger household head. A female headed household is 19% less likely to have off farm work. The accessibility of the village also increases the likelihood of being active on the labour market.

Table 2: Population pressure directly and indirectly affects the use of inputs and engagement in the labour market

	Livestock	Fertilizer	Labour	Off-farm/non-farm work
	OLS	Probit	Probit	Probit
Population pressure: direct effect				
Population density (100 persons/km²)	-0.0303***	0.999***	0.201*	0.0842**
(Population density)²		-0.107***	-0.0181	
Land: indirect effect				
Land (ha)	0.0967***	0.256***	0.230***	-0.0194
Farm and household characteristics				
Age household head	0.00325	-0.0236*	-0.0200*	0.00892
Age²	-0.0000290	0.000198	0.000175	-0.000204*
Female headed household	-0.0533**	0.0348	0.205**	-0.478***
Household size	0.0272***	0.0168	0.0384**	0.0608***
Adult sons	0.0733***	0.0685	0.0516	0.0890*
Education household head (0-2)	0.0262**	0.153***	0.197***	0.225***
Share land in marshes	0.369***	0.505	0.867**	-0.691**
Share land double cropped	0.0475	-0.367***	-0.267**	-0.0438
Regional characteristics				
Distance to capital (km)	-0.000599	-0.0152***	-0.00262*	-0.00203
Accessibility of nearest village (0-5)	0.00513	-0.0347	-0.00447	0.106***
Provincial rainfall (mm³)	-0.000018	0.000196	-0.000388***	0.000141
Elevation above sea level (m)	0.000392***	0.000549**	0.000030	0.000135
R^2	28%			

***,**,* significant at 0.01, 0.05,0.10 levels, respectively; Regional dummies included, but not reported; n=2050

In table 3, we estimate the association between population pressure and yields, food production and farm income with SUR. We found evidence that population density is positively associated with higher yields, but this positive effect is not sufficiently strong to avoid a decline in food production per capita and a stagnation of total income with rising population pressure.

Yields show a non-linear association with population density. Keeping all other variables constant, yields increase with population density up to 561 persons/km² and decrease thereafter (table 3, column 1). This positive effect of population density on yields is further enforced by a strong, negative association between yields and landholdings. An 1 ha increase in land is associated with a decrease in yields of 18%. Hence, the well-known inverse productivity-size relationship also holds in Burundi and is the same order of magnitude as in many other African countries (Larson, Otsuka, Matsumoto, & Kilic, 2014). As a consequence, rising population pressure reduces landholding size directly, but indirectly increases yields. There is, however, a positive correlation between owning livestock and yields and this correlation indirectly reduces the positive association between population pressure and yields. The other inputs, i.e. use of fertilizer, use of hired labour and off/non-farm employment are not significantly correlated with yields. Derivation of the total effect shows that an increase of population density by 100 persons/km² is on average associated with a 10% increase in yields. However, the effect is much stronger (+20%) in the first quartile and almost zero in the fourth quartile. This suggests that the most densely populated regions of Burundi have reached the limits to intensification in terms of yields per ha. Other important correlates of yields are the share of land in the marshes and the share of double-cropped land.

Food production per adult equivalent increases up to 354 persons/km² (table 3, column 2), but decreases thereafter. The indirect, negative effect of population density on food production through landholdings, livestock and non/off-farm employment outweighs the positive indirect effect of using more fertilizer and labour. As a result the total effect of increasing population pressure on food production is only positive in the first quartile and is close to zero or negative in the other quartiles. For instance, an increase of population density of 100 persons/km² is associated with a 9% decrease in food production in the fourth quartile of population density.

There is no significant direct effect of population pressure on net income. Households in densely populated regions partially manage to overcome declining food production through income from non- and off-farm employment. This is confirmed by the fact that households active in the labour market have an income that is 45% higher than households that only work on their own farm. Nevertheless, the positive effect of off-farm employment on income in densely populated regions disappears because of the large and negative association between landholdings and net income. Overall, the total effect of population pressure on net income is practically zero, indicating that net income is neither lower nor higher in more densely populated regions.

Table 3: Results for outcome variables estimated with SUR

	Yield (kg/ha)	Food production (cal/AE)	Net income (cal/AE)
Population pressure: direct effect			
Population density (100 persons/km²)	0.279***	0.148***	0.0310
(Population density)²	-0.0284***	-0.0203***	
Land: indirect effect			
Land (ha)	-0.183***	0.412***	0.358***
Inputs: indirect effects			
Livestock (TLU)	0.0736***	0.148***	0.113***
Applies fertilizer (*yes=1)*	0.0149	0.118*	-0.0696
Hires labour (yes=1)	0.0681	0.354***	0.253***
Engages in off-farm work (*yes=1)*	-0.0276	-0.0825*	0.374***
Farm and household characteristics			
Age household head	0.00507	0.0191**	0.00806
Age²	-0.0000940	-0.000194**	-0.000104
Female headed household	-0.122**	-0.0557	-0.141**
Household size	0.00277	-0.0876***	-0.079***
Adult sons	0.0434	-0.0608	-0.0689
Education household head (0-2)	0.00683	0.0378	0.0575
Share land in marshes	0.907***	0.539**	0.593**
Share land double cropped	0.488***	-0.0271	-0.0761
Regional characteristics			
Distance to capital (km)	0.00818***	0.0116***	0.0117***
Accessibility of nearest village (0-5)	-0.0166	-0.0245	-0.0222
Provincial rainfall (mm³)	-0.000216**	-0.000368***	-0.000296***
Elevation above sea level	0.000339**	0.000199	0.000340*
R^2	21%	36%	31%

***,**,* significant at 0.01, 0.05,0.10 levels, respectively; Regional dummies included, but not reported

When calculating net income 41 households had a negative income and were excluded from the analysis; n=2009

Table 4: Direct and indirect effects of population pressure on inputs and outputs for successive quartiles of population densities

		First quartile (161 persons/km²)	**Second quartile** (266 persons/km²)	**Third quartile** (373 persons/km²)	**Fourth quartile** (508 persons/km²)
Livestock	**Total effect**	***-0,042***	***-0,037***	***-0,037***	***-0,035***
	Direct	-0,030	-0,030	-0,030	-0,030
	Indirect	-0,012	-0,007	-0,007	-0,005
Fertilizer	**Total effect**	***0,163***	***0,155***	***0,072***	***-0,041***
	Direct	0,175	0,162	0,079	-0,036
	Indirect	-0,012	-0,007	-0,007	-0,005
Labour	**Total effect**	**0,044**	**0,033**	**0,017**	**0,001**
	Direct	0,057	0,041	0,026	0,007
	Indirect	-0,013	-0,009	-0,008	-0,006
Off/non-farm work	**Total effect**	***0,034***	***0,034***	***0,034***	***0,034***
	Direct	0,033	0,034	0,034	0,033
	Indirect	0,001	0,001	0,001	0,000

Yields	**Total effect**	***0,212***	***0,143***	***0,080***	***-0,003***
	Direct	0,188	0,128	0,067	-0,009
	Indirect	0,024	0,015	0,013	0,006
Food production	**Total effect**	***0,062***	***0,033***	***-0,022***	***-0,088***
	Direct	*0,083*	*0,040*	*-0,003*	*-0,058*
	Indirect	-0,022	-0,007	-0,019	-0,030
Income	**Total effect**	***-0,002***	***0,012***	***0,017***	***0,027***
	Direct	0,031	0,031	0,031	0,031
	Indirect	-0,033	-0,019	-0,014	-0,004

Coefficients of fertilizer, labour and off-farm work represent the change in probability of a positive demand for these inputs if the population density increases by 100 persons/km². All other coefficients represent semi-elastictities.

Generally, the strength of the negative association between population pressure and well-being is smaller with the formal regressions (table 4) than the more informal graphical analysis (figure 5). For instance, while figure 5 clearly shows decreasing household incomes with increasing population density, this association disappears in the formal regression (table 4, last row). It turns out that the regional fixed effects, that were included in all regressions, partially captured the detrimental impact of population pressure on well-being. When excluding the regions and the distance to the capital as explanatory variables in the regressions, the negative effect of population pressure on the three outcome variables was more pronounced (results not reported, but available upon request). For instance, an increase by 100 persons/km² is now associated with a 9% decrease in net incomes. Regions with a higher average population density are thus also the regions with the lowest average yields, food production and net incomes. This may be because we do not capture all sources of income in some of these regions (e.g. income from cash crops), but it is likely that part of the effect should be attributed to high population pressure. As a result, our results may, if anything, underestimate the negative impact of population pressure on well-being. Our estimates are thus conservative and the 'true' negative impact of population pressure is likely to be even larger.

4. Discussion and conclusions

Our results suggest that Malthusian and Boserupian processes co-exist. As predicted by Boserup, increased population pressure reduces landholdings, which induces land intensification through a higher usage of fertilizers and labour. Livestock, on the other hand, is less common in densely populated regions and this limits the availability of manure. In densely populated regions more households diversify out of agriculture. However, when examining associations between population pressure and yields, food production and income, Malthusian forces seem to be equally or even more important than Boserupian intensification. While yields increase substantially with increasing population pressure at relatively low population densities, they do not seem to continue to increase in regions with a population density of more than 500 persons/km². At the same time, food production per adult equivalent seems to decrease in regions with population densities of more than 350 persons/km²: the higher yields per hectare no longer compensate for the smaller landholdings. Examining net income, we found that income from off- and non-farm sources is more important in densely populated regions and partially compensates for declining food production. However, net incomes are definitely not higher in densely populated regions and the evidence suggest that they decrease with mounting population pressure . This evidence suggests that, given currently available technology in Burundi, there are limits to further land intensification. This is in line with findings from the literature that also found increasing land intensification and yields up to a population density of 450 to 600 persons/km² and stagnating net incomes (Jayne et al., 2014)

Our study has the merit of quantifying adaptation to increasing population pressure in an under-studied region, Burundi, a country known for its extremely high – and still increasing - population densities. Although concerns about endogeneity remain, the correlation between population pressure and key variables of the Burundian agricultural system merit attention because they are of practical value for policymakers in Burundi and can inform the larger debate about the potential for land intensification in Africa. Nevertheless, several limitations to the study need to be recognized. First, although we attempted to disentangle direct and indirect effects of population pressure on agriculture, many of the effects remain hidden within a 'black box'. For instance, we found that an increase of 100 persons/km² in population pressure in regions with a population density below 200 persons/km² directly increases yields by 19% but the processes behind this direct effect remain unclear. Often, these indirect effects are attributed (although without much evidence) to a better institutional environment in more densely populated regions, leading to lower transaction costs for inputs, better access to information, more secure land rights, etc. Similarly, the indirect effects of population pressure on yields can mainly be attributed to the negative correlation between landholdings and yields. Again, the underlying mechanisms behind this inverse productivity-size relationship are unknown. At the same time, the indirect, and well-understood pathway of increasing land productivity through increased use of labour and fertilizer plays only a minor role in explaining total effect of population density on yields. As we did not have access to panel data or data on family labour, we were not able to examine whether fields are more intensively cultivated in densely populated regions, which would partially explain higher yields in these regions. Nevertheless, some previous studies using panel data found that the direct effect of population density on yields and income is much more important than the indirect effect (Muyanga & Jayne, 2014). This suggests that farmers adopt other, more subtle strategies to adapt to local, adverse conditions, which have not been captured in this study. Perhaps, only qualitative research can shed light on these subtle processes. In our view, identifying the processes behind land intensification is a key issue for policymakers, extension services and the academia that deserves further quantitative and qualitative research.

This brings us to a more fundamental question: can a Malthusian crisis empirically be identified *ex-ante*? To some extent, Boserup's hypothesis is an identity, i.e. a relationship that will always hold: as long as there is no crisis, food production – or at least food consumption - will grow at more or less the same pace of the population. A Malthusian process, on the other hand, is only clearly discernible when a crisis – be it a famine or a civil war – erupts. In this view, it is not surprising that some studies use a Malthusian framework to explain a crisis *ex-post* (see for instance: André & Platteau, 1998; Komlos, 1989), while few empirical studies find evidence of an imminent Malthusian crises *ex-ante*. If a new, serious conflict were to erupt in Burundi, many researchers would cite pressure on land as one of the key underlying drivers, while a successful green revolution in Burundi would be explained as an example of Boserup triumphing over Malthus. In a similar vein, even though most empirical studies in the special issue of Food Policy about the role of growing populations on land intensification, as well as this study, found evidence of land intensification up to a threshold of 400 to 600 persons/km² this does not necessarily mean that a vicious Malthusian circle will begin beyond this level of population density. In all these case studies this threshold is above the 75th percentile of the distribution of population density and thus only involves a relatively small fraction of the population, who may indeed be less well-off than households in less densely populated regions, but nonetheless perhaps still relatively far from a Malthusian crisis.

These theoretical arguments notwithstanding, it is evident that population pressure and competition for scarce resources are serious threats to the agricultural sector and society at large in Burundi, but whether the future will unfold according to the predictions of Boserup or those of Malthus remains an open question. As emphasized in much of the literature on rural development, avoiding a Malthusian catastrophe will require both augmenting land productivity and developing a non-farm economy which can pull rural households out of agriculture (Haggblade, Hazell, & Reardon, 2010). This is, of course, easier said than done. But the *status quo,* i.e. a growing population without a commensurate increase in food production, can never be sustainable in the longer term.

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