WPS7290

Policy Research Working Paper 7290

Costs and Benefits of Land Fragmentation

Evidence from Rwanda

Daniel Ayalew Ali
Klaus Deininger
Loraine Ronchi

WORLD BANK GROUP
Development Research Group
Agriculture and Rural Development Team
June 2015

Policy Research Working Paper 7290

Abstract

This paper disentangles different aspects of land fragmentation and its impact on the efficiency of resource use. The paper uses information on the incidence of crop shocks to assess whether fragmentation provides benefits in reducing risk and parcel coordinates and terrain-adjusted travel times between parcels to more precisely account for the associated costs in 2010/11 data from Rwanda. While fragmentation increases the time required to move between a household's parcels, this does not appear to affect overall technical efficiency on the farm. Fragmentation rather reduces the incidence of crop shocks and increases yields and productive efficiency. In Rwanda's setting, interventions to reduce fragmentation may, therefore, be ineffective or counterproductive.

This paper is a product of the Agriculture and Rural Development Team, Development Research Group. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The authors may be contacted at dali1@worldbank.org, kdeininger@worldbank.org, and lronchi@worldbank.org.

Costs and Benefits of Land Fragmentation: Evidence from Rwanda[¶]

Daniel Ayalew Ali, Klaus Deininger, Loraine Ronchi

World Bank, Washington DC
dali1@worldbank.org, kdeininger@worldbank.org, lronchi@worldbank.org

JEL Classification: O13, Q12, Q15, Q16

Keywords: land fragmentation, productive efficiency, yield, crop shocks, Rwanda

[¶] We would like to thank the UK Department for International Development and the Knowledge for Change Program for funding support. We thank Rodney Dyer, Sion McGeever, and Cyriaque Harelimana for initiating and supporting data collection as well as the National Land Centre (now Rwanda National Resource Authority) in Kigali, especially Emmanuel Nkurunziza, Didier Sagashya and Thierry Ngoga for their overall support. We are also very grateful to Siobhan Murray for an excellent Arc GIS related support.

1. Introduction

Concerns about land fragmentation, i.e., the fact that the cultivators' land is distributed among many parcels or fragments, often of very small size, as a constraint to agricultural productivity have long been prominent in the policy debate, especially in land-scarce environments. Practices of equal inheritance among siblings or kin in the presence of high population growth or land reforms that awarded many parcels of different types imply that households may be involuntarily endowed with large numbers of parcels and fragmented holdings. Illiquid land markets and high transaction costs may then prevent them from consolidating fragments to attain larger holdings and adopt 'modern' practices of cultivation. Thus, it is often argued that public action to solve the underlying collective action problems and help move towards a pattern of land holding that is more viable economically would be desirable.

This narrative seems at odds with evidence in the literature from many non-mechanized settings where having a large number of diverse parcels may be used to exploit micro-variation in soil quality or climate and thus minimize exposure to production risk. As long as labor costs are modest or work is performed by family workers whose shadow wage may be below the market wage, the need to physically travel between spatially dispersed parcels may also be modest. This could mean that fragmentation brings benefits (due to risk diversification) as well as costs (due to the higher labor requirements for moving between parcels) and that the balance between these will depend on the specific environment, in particular the opportunity cost of labor, the level and potential for mechanization, levels of production risk, and availability of insurance. And, while fragmentation may limit the scope for mechanization, especially if it results in parcel sizes (or shapes) below the minimum at which use of mechanical equipment such as large ploughs or harvesters makes sense, prevailing factor price ratios may imply that this is not an economically desirable option in any event.

The fact that consolidation has been widely promoted even in low-wage environments suggests that empirical investigation paying greater attention to both costs and potential benefits from fragmentation is desirable. We use Rwandan data to contribute to this discourse. Information on whether or not production on a parcel was affected by exogenous shocks such as pest or insect attacks, droughts, or floods is used to explore for presence of risk diversification benefits associated with a more fragmented pattern of land holding. GPS information on altitude and location for each of a household's parcels, projected on a detailed digital elevation model (DEM) of the country, allows us to compute travel times between parcels or the homestead taking account of differences in altitude which, in Rwanda's hilly terrain, are not negligible. Travel time between all parcels thus calculated as well as different measures of fragmentation is included in a yield or frontier production function to explore impacts of fragmentation on output and the efficiency of agricultural production.

Results support the notion that fragmentation helps manage production risk; having an additional parcel is estimated to reduce the likelihood of being affected by a crop shock by about 10 percentage points. At the same time, even though fragmentation carries costs in terms of increasing travel time between parcels, no negative impact on yield or technical efficiency of production is discerned. Total travel time to visit all parcels is estimated to have a positive rather than a negative impact on yield and, to some extent, technical efficiency. If our results are correct, economic factors are likely to be more important in driving future changes in fragmentation than regulatory and administrative efforts. Consolidation efforts thus appear to have promise (and be sustainable in the long term) only if they are based on a careful assessment of the underlying economic factors. Further research on how the benefits and costs of land fragmentation change with the economic environment and the scope and limits of land markets to contribute to a more consolidated pattern of land holdings will be required to help decide if and when consolidation initiatives may be warranted and sustainable.

The paper is structured as follows. Section two reviews some of the literature to lay out the conceptual framework, measurement issues, and introduce the econometric approach. Section three describes the data, provides descriptive statistics at holding and parcel level, and explores the extent to which expansion of holdings through land market transactions may underlie some of the high levels of fragmentation observed in the data. Section four presents results regarding risk diversification benefits from land fragmentation, yield functions, and estimates of technical efficiency using a frontier production function. Section five concludes by drawing out implications for policy both in Rwanda and beyond.

2. Measurement, conceptual framework, and econometric approach

The literature highlights that fragmentation of land holding structures may be exogenously imposed, e.g., by regulation of inheritance in the presence of illiquid land markets. Alternatively, it may result from a conscious choice by producers who, at any point in time, trade off associated risk-reduction benefits against costs in terms of higher travel time and potentially more limited scope for mechanization. This implies not only that the impact of fragmentation may vary over time, but also that exploring its impact will require accounting for this trade-off and that a failure to do so may underpin the ambiguous results from many studies. We discuss how to measure each of these elements and describe our approach to assessing costs and benefits from fragmentation in Rwanda using yield regressions and a stochastic frontier production function.

2.1 Conceptual issues and existing evidence

Fragmented land holding structures may be exogenously imposed by inheritance rules under high population growth (Baker and Miceli 2005; Platteau and Baland 2001) or the modalities of plot

individualization in the transition from centrally planned economies (Tanaka 2007). Alternatively, they may be chosen by producers who trade off benefits against costs of fragmentation. A key benefit is the ability to diversify the plot portfolio to include plots with different attributes (cropland, pastures, orchards, vineyards) so as to reduce exposure to price risk or variability of production due to flood, drought, or pests (McCloskey 1975) or ease bottlenecks and smooth out seasonal variability in labor demands (Fenoaltea 1976). Costs accrue because fragmented plot holdings may preclude use of machinery and, depending on the location of plots, may require spending more time to move between plots (Bentley 1987). Ascertaining the impact of fragmentation will thus require proxies for associated costs as well as benefits.

Studies that include only the number of plots cultivated or the Simpson index of land fragmentation that ranges from zero to one, with higher values corresponding to higher fragmentation but fail to account for risk-reduction benefits, often find negative effects of fragmentation. In 5 Chinese provinces (Jilin, Shandong, Jiangxi, Sichuan, Guangdong), a production function for a sample of some 1,000 farmers with 5 key corps (maize, early and late rice, wheat, and tubers) in 1994 suggests a significant negative impact: exogenous addition of one plot is estimated to reduce output by 2 to 10 percentage points depending on the crop (Wan and Cheng 2001).[1] In Bangladesh, for a small sample of 298 farm households with an average of 4.4 parcels per holding in 2000, a frontier production points towards a negative productivity- and efficiency-effects from plot fragmentation (Rahman and Rahman 2008). Estimating a yield function on a small panel from North Vietnam for 200 farmers on very fragmented holdings (mean and median plot numbers of 6.84 and 6 and Simpson index of 0.59 and 0.68, respectively) in 2000/1 similarly suggests that number of plots has a statistically negative effect on yield and increased family labor use and other money expenses (Hung *et al.* 2007). On the other hand, a small sample (227 households) from Hubei province in China finds that the number of plots had no significant effect on crop production (as measured by a production function). Moreover, a program to reduce land fragmentation did not achieve its main goal, possibly because with relatively abundant labor, the scope to use any labor savings in other tasks was limited and low levels of technology implied significant fragmentation-related benefits in terms of risk-reduction (Wu *et al.* 2005).[2]

One way of accounting for potential benefits from fragmentation more explicitly is to explore impacts on variability of output in a panel setting. Kawasaki (2010) applied this approach together with a cost stochastic frontier function on a large panel of Japanese rice farmers (18,000 farms per year from 1995-2006 rice production cost statistics) who cultivate a mean of 4 parcels with a Simpson index of 0.8 together with a

[1] The magnitude of these effects is used to argue that efforts to eliminate fragmentation, either by improving functioning of factor markets or by programs aimed specifically at land consolidation, would be worthwhile (Chen *et al.* 2009).
[2] This mirrors evidence from Albania where fragmentation does not seem to negatively affect output and crop abandonment due to ill-functioning land market institutions, in particular the registry seems to be a more potent factor in reducing land use efficiency (Deininger *et al.* 2012).

cost function. The results show that parcel number and Simpson index increase cost inefficiency and average cost but reduce variance of output per hectare. In the case of Japan, high wages and well-functioning insurance markets implied that costs associated with fragmentation outweighed the benefits but this may well be different in other settings (Kawasaki 2010). In Bulgaria, fragmentation (measured by the Simpson index) was found to reduce farm profitability but to boost richness of species as measured by a biodiversity index (Di Falco *et al.* 2010).

If fragmentation increases cost of production due to the need to move between plots and/or the homestead, it may be desirable to measure these costs more explicitly. Indeed, studies going in this direction suggest not only that distances are often highly relevant, but also that they are often very weakly correlated with more traditional measures of fragmentation. A cost function for 331 rice farmers on highly fragmented holdings (more than 7 plots on average with a Simpson index of 0.73 and a mean homestead-parcel distance of 16 min.) in three villages of Jiangxi Province in China suggests that cost of production is little affected by the Simpson index, increases with mean homestead-plot distance, and falls somewhat with farm size (Tan *et al.* 2008).[3] A stochastic frontier production function using these data suggests that mean plot-homestead distance reduces technical efficiency whereas number of plots (and mean plot size) both are associated with higher levels of technical efficiency (Tan *et al.* 2008).

The relative importance of fragmentation-induced costs and benefits will also depend on wages, the scope for mechanization, and availability of other options to reduce or insure against risk. If labor costs are high and mechanization widely practiced, the costs imposed by small or highly fragmented plots can easily outweigh potential benefits. On the other hand, if options to diversify risk via insurance are limited and labor cost low, benefits from fragmentation may outweigh associated costs (Sengupta 2006). This explains why returns of programs to consolidate holdings, often together with land use planning, in developed countries are reported to have been high (Simons 1987). It also suggests that impacts may change with factor price ratios in the course of economic development. For example, in India it is argued that traditionally productivity losses associated with land fragmentation have been modest and benefits substantial (Heston and Kumar 1983) but this may change as cost of labor relative to machinery increases (Foster and Rosenzweig 2010).

Study of fragmentation impacts in Africa, though not always fully conclusive, highlights the cost-benefit trade-off and yields qualitatively similar conclusions. Data for a small sample (150 and 80 households per region) from three regions in Ghana suggest little, if any, correlation between the level of fragmentation and mean plot-homestead distance.[4] Yield equations provide little evidence of land fragmentation having

[3] The Simpson index was found to increases labor cost but reduces costs of fertilizer, seed, and oxen or tractors costs.

[4] Two regions (Analoga and Wassa) are highly fragmented (median number of 5 parcels and Simpson index of 0.77 and 0.66, respectively). On the other hand, fragmentation is very low in the third region (Ejura), with a median parcel number of one and a mean Simpson index of 0.23. However, the correlation between average parcel distance and fragmentation in consistently low and average distance between homestead and parcels is greater in the latter than the former (3.5 km vs. 1.8 km).

adverse effects on land productivity (Blarel *et al.* 1992). Despite Rwanda is characterized by higher levels of fragmentation (6 parcels with a median Simpson index of 0.66 per household), there is no significant relationship between levels of fragmentation and yields, irrespectively of whether efforts are made to control for endogeneity. While pointing towards risk reduction as a potential reason for persistence of fragmentation, links between fragmentation and variability of output remain tentative at best (Blarel *et al.* 1992).

2.2 Measurement issues and analytical approach

With the highest population density in Africa (384 inhabitants/km^2 overall and 526/km^2 of agricultural land) and some 85% of the population having agriculture as their main income source, effective land use and land-related investment are critical for poverty reduction in Rwanda (Republic of Rwanda 2009). In 2008, the average household had only 0.72 ha of land, below the threshold of 0.75 ha estimated to be required to meet a family's subsistence needs with available technology. Negative impacts from population growth-induced fragmentation are widely viewed as having led to serious environmental challenges (Republic of Rwanda 2004) and even conflict (Andre and Platteau 1998). In fact, to stem fragmentation, the law prohibits fragmentation of land below a size of 1 ha,[5] though more than 90% of parcels fall below this size (Ali and Deininger 2014).

A measure of fragmentation that is widely used in the literature, in addition to the number of parcels, is the Simpson index, defined as $SI=1- \Sigma a_i^2 / (\Sigma a_i)^2$ where a is the area of parcel $i=1,..,n$. This index varies between 0 and 1 with zero for a completely consolidated operation. To account for the ability to grow a larger number of crops as one of the potential benefits of fragmentation, we complement this with the Shannon crop diversity index, defined as $SH=- \Sigma (P_i * \ln P_i)$ where P_i is the share of area covered by a specific crop. This index which combines both richness of type (number of crops) and relative abundance (land allocation among crops), equals zero if there is only one crop (i.e., no diversity) and increases with the number of cultivated crops as well as with more even shares by different crops, reaching its maximum when crops are cultivated in equal shares (i.e., $P_i=1/J$) where J is the maximum possible number of crops cultivated. Finally, parcel altitude and its variability provide a third indicator of fragmentation.

As they do not incorporate information on plot location, the above measures are at best imperfect proxies for the cost of having to travel between plots. That is, households with given number and size distribution of plots will have the same Simpson index irrespectively of whether these plots are located next to each other and the homestead or kilometers away and separated by rivers or mountain ridges. In fact, some surveys have included questions regarding travel time between homestead and plots to fill this gap. We go

[5] The 2005 Organic Land Law (OLL) prohibited sub-division of agricultural land parcels less than one ha and required approval for any subdivision of parcels between 1 and 5 ha. The prohibition of sub-division is upheld in the 2013 OLL revision.

beyond this by recording parcel-level GPS coordinates for all of a household's parcels in the cell of residence[6] so as to allow computation of the mean Euclidian distance between homestead and parcel, the length of the path that has to be traversed to visit all parcels, and the time required to walk these. Use of the latter is justified because, in Rwanda's hilly terrain, a straight line will often not be the most effective way of getting from location A to location B. To implement this, we use the publicly available Aster Global DEM to derive a 30 by 30 meter slope grid and apply appropriate friction parameters to compute the least cost walking distance between any two points.[7] Figure 1, which displays the DEM together with the location of the homestead and parcels for one of our sample households with 4 parcels (at an altitude between about 1,500 and 2,100 m), one of which at the homestead, illustrates this procedure graphically. It is easily verified that the straight line or Euclidian distance (in red) may be different from the least cost path between any pair of parcels (in blue). Figure 2 displays the minimum path to visit all the household's parcels starting and ending at the homestead graphically.

2.3 Econometric approach

Before considering the impact of fragmentation on productivity or farm efficiency, it is helpful to first identify the extent to which fragmentation helps Rwanda's smallholder farmers manage risks. To this end, we use responses to the question of whether a crop shock was experienced on a given parcel to compute the share of land used by a household that was affected by a crop shock.[8] We then regress this variable on indicators for fragmentation (number of parcels, Simpson index, Shannon index, number of crops), farm-level characteristics such as the coefficient of variation in parcels' altitude, the Herfindahl index of diversity in soil quality and slope[9], as well as standard attributes including size and composition of the household and age and education of the head to obtain a reduced-form estimate of the extent to which any of these factors may help to reduce the likelihood of being affected by a crop shock.

We then explore effects of land fragmentation on agricultural productivity by estimating a reduced form yield equation to measure the direct impacts of land fragmentation on the value of crop output per unit of cultivated land. Assuming a Cobb-Douglas production function, the yield equation is:

$$\ln\left(\frac{Y_{it}}{A_{it}}\right) = \beta_0 + \beta \ln A_{it} + \theta' W_{it} + \phi' F_{it} + V_t + \epsilon_{it}, \quad (1)$$

[6] Expanding beyond the cell would have been too costly.
[7] The Aster model is available at http://asterweb.jpl.nasa.gov/. We use Tobler's (1993) hiking function—estimated using Imhof's (1950) empirical data—that models for walking on footpath by taking into account the slope of the terrain. It is an exponential function of slope (S), defined as W = 6*exp{-3.5*abs(S + 0.05)}, that takes an average speed of 5 km/h on a flat terrain.
[8] The question was specifically phrased as: "While in the field or at the time of harvest, was there any crop damage/loss?"
[9] The Herfindahl index (fractionalization index for soil type and topography) that captures the probability that two randomly selected parcels from a given household will not belong to the same soil type or topography is defined as H=$\sum_{i=1}^{n} p_i(1-p_i)$ where i indexes groups, n is the total number of groups (soil type or topography) in each household and p_i is the share of group i in the household (i.e., the area share of a given soil type or topography). It ranges between zero and one, moving from a homogenous to a more diversified land type.

where Y_{it} is the total value of crop output of household *i* at time *t*; A_{it} is total cultivated area in hectares; W_{it} is a vector of area weighted parcel characteristics including subjective land quality measures (soil type, topography, irrigation), crop dummies, and a measure for whether or not parcel-specific crop shocks were experienced; F_{it} is a vector of land fragmentation indicators at household level (number of parcels, Simpson fragmentation index, Shannon crop diversity measure, or the time taken to traverse the minimum cost path between the homestead and all parcels); V_t is a time-varying village specific fixed effects; *β, θ* and ϕ are parameters to be estimated and ϵ_{it} is a random error term.

To allow for the possibility that land fragmentation affect the efficiency of the production process overall, we complement this approach with a stochastic frontier production function (Wan and Cheng 2001) based on a Cobb-Douglas functional form. The stochastic production frontier model to be estimated for each household *i* can be expressed as.

$$\ln Y_{it} = \beta_0 + \beta' \ln X_{it} + \gamma' D_{it} + \theta' W_{it} + V_i + T + v_{it} - u_{it}, \tag{2}$$

and

$$u_{it} = \phi' F_{it} + \delta' Z_{it} + \xi_{it} \tag{3}$$

where Y_{it} is the total value of crop output for household *i*; X_{it} is a vector of traditional inputs including land, labor, chemical fertilizer, manure and pesticides; D_{it} is a vector of indicator variables to account for zero values of non-labor variable inputs (Battese 1997);[10] W_{it} is a vector of area weighted parcel characteristics and environmental conditions (subjective soil type and topography assessments as well as tenure, years of possession, parcel location, access to water and extension services, seed type, crop choice, incidence of crop specific shocks);[11] V_i is a vector of village dummies; *T* is time dummy; v_{it} is a random error to account for statistical noise distributed as $N(0, \sigma_u^2)$; u_{it} is a non-negative random variable associated with technical inefficiency; and *β*, *γ*, and *θ* are parameters of the non-stochastic component of the production frontier.

We assume that the technical inefficiency component, u_{it}, in equation (3) is distributed as $N^+(\phi' F_{it} + \delta' Z_{it}, \sigma_v^2)$ truncated at zero from below where Z_{it} is a vector of indicators of managerial ability (gender, age and education of the household head, access to extension and improved seeds), the share of land affected by crop shocks; F_{it} is set of indices measuring different aspects of land fragmentation as above; ϕ and δ are vectors of parameters to be estimated; and ξ_{it} is the unobserved random error term. Equations (2) and (3) are estimated simultaneously together with the variance parameters $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\gamma = \sigma_u^2/\sigma^2$ that take a value between zero and one based on the generalized log-likelihood function found in the literature (Kumbhakar *et*

[10] Following the procedure proposed by Battese (1995), variable inputs with zero values are transformed into logarithm form as $\ln\{\text{Max}(X_{it}, D_{it})\}$ where D_{it} is a vector of dummies taking a value of one for zero observations of non-labor inputs.
[11] For empirical examples on the choice of parcel characteristics and environmental conditions that are directly incorporated in the non-stochastic component of the production frontier, see Coelli *et al.* (1999) and Sherlund *et al.* (2002).

al. 1991). This procedure produces consistent estimates as it explicitly accommodates the non-negative nature of the technical inefficiency in the likelihood function, thus allowing us to make inferences on the impacts of fragmentation on technical inefficiency.

3. Data and descriptive evidence

We describe our panel sample of small Rwandan producers and descriptive evidence of household and parcel characteristics with different levels of fragmentation. Data are suggestive of fragmentation helping to reduce risk and diversify crop output. Comparing GIS/DEM based parcel-parcel and parcel-homestead distances for households in autarky and those participating in land rental or sales markets and, more importantly, own vs. rented or purchased parcels by the same household, suggests that survey responses may be biased and that, while land purchase may significantly increase distances between parcels (though by a small amount), there is no evidence of rental having any significant impact in this respect.

3.1 Data sources and household/parcel characteristics

To provide evidence on fragmentation and production outcomes, we use a nationally representative two-round panel survey of 3,600 households in 300 randomly selected villages (see figure 3 for location of sample cells) conducted in 2010/11 and 2011/12.[12] Detailed information on crop production was collected at parcel level and GPS readings were taken for the homestead and all parcels in the cell of a household's residence. Key descriptive statistics are illustrated in table 1, overall (col. 1) and for households in terciles of the parcel distribution (cols. 2-4) where stars indicate the significance of differences between the 1st and the 2nd and 3rd terciles, respectively.

While mean holding size is only 0.81 ha, 0.61 ha of which is cultivated, the average sample household has almost 5 parcels on which some 4.5 crops are grown, a figure increasing to 8.3 parcels and 5.6 crops for the top tercile (see appendix figure 1 for the distribution of number of crops cultivated). Parcels have been possessed for 17.91 years on average, 8.2% are located in wetland, 5.5% have access to irrigation, and 36% and 16% are reported to be of high or medium soil quality. About 50% are cultivated with grains, 26% with tubers, 23% with trees, and the remainder of about 1% with vegetables. While those with more parcels cultivate slightly more tubers and less grains, mean output value per ha remains at some US$ 559 throughout. There is also no difference in the share of parcels (some 10%) benefiting from extension input. With a high overall share of female headed households being in the bottom tercile, they have significantly fewer parcels than male headed ones. Households with more parcels are slightly larger, with 2.3 1.7, and 0.98 members below 14, between 14 and 35, and between 35 and 60, respectively and have marginally

[12] The panel survey (i.e., baseline and its follow up) is designed for assessing the impact of Rwanda's program of land tenure regularization (LTR) and was managed by the World Bank with support from the UK Department for International Development (DFID) and International Growth Centre (IGC).

higher levels of education (64% and 9.6% having completed primary and secondary education, respectively, compared to averages of 57% and 7%).

Regarding measures of fragmentation, the mean self-reported distance between homestead and parcel is 0.17 hours, from 0.12 hours in the bottom to 0.21 hours in the top tercile, slightly higher than the computed minimum cost path of 0.11 hours (0.08 to 0.14). Total travel time from the homestead to visit all parcels and then return home is 0.82 hours overall, from 0.38 hours for the bottom tercile to 1.37 hours for the top one, an increase that is markedly higher in relative terms than the increase in cultivated (0.53 to 0.76 ha) or owned area (0.59 to 1.23 ha). Simpson and Shannon indexes peak at 0.7 and 1.4 (appendix figures 2 and 3). As can be seen in appendix figure 4, the association between holding size and number of parcels is weak, i.e., it seems that a desire to expand the size of cultivated area is not the primary motivation for increasing the number of parcels cultivated but that other reasons such as crop diversification could play a significant role. The mean parcel is 0.19 ha and 28% of households had experienced a crop shock during the period under concern.

3.2 Parcel distances between and within households

To explore potential links between land market participation and fragmentation in more detail, table 2 compares key distances for land rental (panel A) and land purchase (panel B) between participants and non-participants and, more importantly, within the same household between owned and rented or purchased parcels. We report the mean walking time between parcels on the fastest path taking into account slopes from the DEM (cols. 1-2), between parcels and the homestead using the least-cost path based on the DEM (cols. 3-4), and walking time between parcels and the homestead as obtained from households' responses in the survey (cols. 5-6).

Two results emerge from this exercise. First, while survey-based estimates of mean walking distance to owned parcels seem to be reasonably close to the ones based on the computed least-cost path, households seem to systematically overestimate the distance to rented parcels. As a result, a significant difference in homestead-parcel distances emerges between owners and renters-cum owners (rows 1 and 2, cols. 5-6) but this is not backed up by figures on the least cost path between homestead and parcels or all parcels computed based on of GIS/DEM information. Similarly, while rented parcels are more distant from the homestead based on owners' estimates (12 vs. 23 min) and GIS/DEM information (10 vs. 16 min), there is no significant difference if the least cost path from rented to owned parcels and between owned parcels is considered. Land rental thus appears to increase homestead-parcel distances, but have no impact on mean distances to be covered between parcels and from a substantive point of view, inclusion of rented parcels in our analysis would not raise any issues. Second, differences are slightly more pronounced for purchased parcels; while there is no statistically significant difference in distance between pure owners and those who

also purchased some parcels, purchased parcels are on average located at a larger distance from the homestead (11 vs. 16 min.) and from other parcels than owned ones, with the mean within-parcel distance increasing slightly from 17 to 23 min.[13]

4. Econometric results

There are three econometric models estimated. First, the risk diversification benefits from fragmentation are supported by a reduced-form regression of crop shocks. Second, a household-level yield function points towards greater fragmentation and crop diversity being associated with higher rather than lower levels of output per hectare with the least cost path that connects all the parcels to the homestead being either insignificant or in some cases even positive. Third, a stochastic frontier production function that accounts for traditional inputs and includes measures of fragmentation as inefficiency parameters, suggests that number of parcels and the Simpson index increase efficiency while distances between parcels have no significant impact, consistent with the notion that the incremental costs it imposes are relatively low, while higher levels of fragmentation reduce it.

4.1 Fragmentation and risk diversification

Results from the reduced-form regression of the share of a household's land subject to a crop shock are reported in table 3. Main independent variables of interest are the Simpson land fragmentation index (col. 1), the number of parcels (col. 2), the Shannon crop diversity measure (col. 3), and the number of crops (col. 4). Point estimates for the coefficients on all of these are negative, suggesting they help reduce the likelihood of crop shocks. At the same time, magnitude and significance levels are slightly larger for proper fragmentation measures compared to indicators of crop diversity with the number of corps grown being insignificant at conventional levels.

Regarding other variables, the coefficient of variation for parcel altitude remains insignificant, suggesting that differences in elevation may likely affect output more through crop choice rather than risk diversification. A higher number of adult members aged 15-35 and 35-60 reduces the likelihood of being affected by crop shocks, most likely by allowing greater attention to crop management. Female headed households are no more likely to be affected by crop shocks than male-headed ones. While the lack of a measure of the severity of the shocks or losses associated with it cautions against over-interpretation and implies that the relationships should be taken as indicative only, the magnitude of fragmentation-related risk reduction effects seems substantial; according to the estimates, adding an additional parcel would reduce the likelihood of shocks as much as an addition of more than 3 adults to the household.

[13] Interestingly, use of survey responses would lead one to underestimate this difference, suggesting that ideally the impacts of fragmentation should be studied using of GIS/DEM-based information.

4.2 Yield regression

Results from the household-level yield regression for the full sample of 6,626 households are in table 4 with number of parcels (cols. 1-3) or the Simpson index (col. 4-6) as key indicators for fragmentation of land holdings. Beyond a basic specification with the DEM/GIS-based distance measure (col. 1 and 4), we introduce the Shannon crop diversity measure (col. 2 and 5) and shares for key crop categories (col. 3 and 6). Coefficients on both the number of parcels and the Simpson index are positive and significant throughout, suggesting that fragmentation improves yields per cultivated area; according to the point estimate, adding an additional parcel would increase yield by between 7 and 9 percentage points, similar in magnitude to half a standard deviation (the standard deviation is 0.246) increase in the Simpson index. A one standard deviation (0.465) increase in the Shannon diversity measure would, according to the estimates, further enhance yields by about 25 percentage points. Interestingly, while total cost distance and its square are insignificant in the specification where the number of parcels is used as the proxy for fragmentation, estimates point towards a positive effect of distance on yield (cols 4-6), up to a distance of 4.7 hours, well beyond the mean observed in the data. A dummy for whether the household has parcels outside the cell is insignificant.[14]

Coefficients on other variables in the regression are in line with expectations. The negative relationship between farm size and gross output that has also been found elsewhere (Ali and Deininger 2014) is clearly visible with a doubling of cultivated area estimated to reduce yield by between 48% and 56%. Having experienced a crop shock is estimated to reduce output by between 21 and 26 percentage points. Soil quality has a clear output-increasing effect with good quality parcels having yield that is higher by some 16% and medium quality ones with output that is higher by 7%, though the latter is only marginally significant. Location in a wetland, a proxy for better access to water, also increases output by between 14% and 16% while irrigation is too rare to have a measurable impact. Output is higher on land that has been held for a longer time; each additional year is estimated to augment yield by 0.4%. Reliance on extension messages is estimated to have a very positive effect increasing gross output by between 17-19%. However, as unobservable attributes such as farmers' ability may affect whether or not extension advice is sought in the first place, this should not be interpreted in a causal sense.

At the household level, higher levels of education clearly enhance crop output, with primary and secondary education increasing yield by 8-9 and 13-15 percentage points, respectively. Access to young family labor augments output; an additional member below the age of 35 is estimated to be associated with an increase

[14] Considering only households who have all of their parcels in the cell significantly reduces the sample size to 3,957. Results for these are reported in the appendix as a robustness check

of about 3% in terms of output per ha. Female headed households obtain yields that are about 18% lower and further exploration of factors that might give rise to this phenomenon would be desirable.

4.3 Frontier production function

While the above findings are consistent with the notion that higher levels of fragmentation allow farmers to diversify risk, the yield function does not control for conventional inputs. If there was a systematic link between levels of fragmentation and farmers' application of such inputs (e.g., if those on fragmented holdings used family labor more intensively), the yield regression would not provide a proper assessment of the impact of fragmentation on productivity. A frontier production function allows controlling for this and assessing whether higher yields are indeed a measure of efficiency.

Results from doing so are reported in table 5. Coefficients for conventional inputs in the top panel are all positive and highly significant. Point estimates for other variables are in most cases similar to what was obtained in the yield function, with the exception of the coefficient on use of knowledge from extension services, suggesting that much of extension's impact on yields may come through more intensive use of conventional inputs. Turning to the second panel which displays relevant inefficiency parameters, we note that higher education clearly enhances efficiency with the point estimate on secondary education close to double that for primary only and female headed households being significantly less efficient than male headed ones. Having experienced a crop shock may reduce efficiency of cultivation beyond its (negative) impact on the production function.

With respect to the fragmentation measures, number of parcels and the Simpson index are estimated to enhance productive efficiency and the Shannon diversity index has a positive effect on efficiency. Consistent with the results of the yield equation approach, total cost distance improves technical efficiency when the Simpson index rather than number of parcels is used as a measure of land fragmentation. This implies that, in Rwanda's current setting, there is little reason to be concerned about fragmentation of holdings being involuntary or excessive; to the contrary in light of the fact that higher levels of fragmentation not only enhance yield, but also increase efficiency of resource use, interventions to reduce it without offering alternatives may not have the desired impact or even run counter to the intent of increasing productivity.

5. Conclusion and policy recommendations

Concerns about involuntary fragmentation and barriers to market-driven consolidation, in particular high coordination costs and insufficiently liquid land markets, have been key factors motivating support for public efforts to consolidate holdings in many parts of the developed world. Although evidence in the literature on impacts of fragmentation is ambiguous and many consolidation programs have not fully

achieved their objectives, a desire to ‘modernize’ agriculture and open the way to large-scale mechanized cultivation has prompted some developing countries to also consider consolidation measures.

In light of high levels of population density, and a large number (4.8 on average) of small (< 0.2 ha each) parcels, Rwanda has taken active measures to increase security and gender equality of access to land. It has also promoted the consolidation of land holdings or prevention of further fragmentation, which has given rise to debate by experts. Many hold that, as in Rwanda, where labor costs are modest, mechanization largely absent, distances from the homestead to fields are small, variability of production high and other mechanisms to diversify risk limited, fragmentation may impose few additional costs but provide tangible benefits.

A nationally representative survey allows us to explore fragmentation-induced effects empirically and, by more precisely measuring travel times between parcels, also contribute to the methodological debate. Both a stochastic frontier production function and a yield function suggest that, by reducing the incidence of production shocks, fragmentation provides tangible benefits without increases in cost or reductions in the efficiency of agricultural production. Prohibiting fragmentation is likely to run counter to strong economic incentives and may thus bring limited benefits or even have unintended negative impacts.

While the specific results obtained here may in part be attributable to Rwanda’s conditions at the time of the data collection, the use of GIS/DEM based between parcels and homestead to parcel distance measures is applicable beyond the case at hand. Although applying it to African settings where, as a result of less severe land pressure and higher labor costs, scope for mechanization may be higher, it could help to better understand the factors at play. In doing so, it could help in understanding not only land markets, but also the factors that may facilitate or constrain use of mechanization.

Table 1: Household level descriptive statistics

Variables	Total	By tercile of parcel distribution 1st	2nd	t-stat	3rd	t-stat
Holding characteristics						
Number of parcels	4.786	2.302	4.416	***	8.316	***
Simpson land fragmentation index	0.523	0.337	0.584	***	0.711	***
Shannon crop diversity index	1.136	0.983	1.159	***	1.315	***
Distance to homestead in hours (self-reported)	0.167	0.126	0.180	***	0.208	***
Minimum cost path to homestead in hours	0.106	0.075	0.112	***	0.140	***
Total cost distance in hours	0.815	0.376	0.834	***	1.367	***
Soil type diversity index	0.194	0.100	0.207	***	0.303	***
Parcel topography diversity index	0.172	0.094	0.183	***	0.265	***
Range of altitude covered in meters	986-2839	986-2799	1158-2833		1150-2839	
Total holding in hectares	0.805	0.588	0.756	***	1.129	***
Total cropped area hectares	0.614	0.531	0.570		0.761	***
Household has parcel outside the cell	0.403	0.235	0.450	***	0.580	***
Share of land located outside the cell	0.074	0.054	0.088	***	0.087	
Area share of rented-in parcels	0.150	0.150	0.173	**	0.129	***
Household-level land use						
Number of crops grown	4.506	3.602	4.534	***	5.653	***
Value of crop output per hectare (US$/ha)	558.7	593.7	536.8		532.12	
Share of land cultivated with extension input	0.103	0.108	0.101		0.098	
Share of land with crop shock	0.275	0.327	0.281	***	0.204	***
Share of total cultivated area with grains	0.501	0.521	0.496	***	0.479	*
Share of cultivated area with tubers	0.262	0.246	0.276	***	0.271	
Share of cultivated area with tree crops	0.225	0.222	0.217		0.237	**
Share of cultivated area with vegetables	0.012	0.011	0.011		0.013	
Parcel characteristics						
Parcel area in hectares	0.194	0.270	0.153	***	0.145	
Average number of years parcel possessed	17.908	19.101	16.564	***	17.516	**
Share of land located in wet land	0.082	0.068	0.080	*	0.101	***
Share of land with access to irrigation	0.055	0.054	0.058		0.055	
Share of high quality land	0.362	0.369	0.353		0.359	
Share of medium quality land	0.155	0.135	0.165	***	0.171	
Share of poor quality land	0.484	0.495	0.483		0.469	
Household characteristics						
Female headed household	0.290	0.368	0.264	***	0.211	***
Head completed only primary school	0.576	0.523	0.584	***	0.637	***
Head completed secondary education	0.066	0.045	0.064	***	0.096	***
Age of household head	46.793	48.176	45.473	***	46.134	
Members aged 14 and less	2.136	1.985	2.140	***	2.328	***
Adult members between 15 and 35	1.605	1.485	1.634	***	1.735	***
Adult members between 35 and 60	0.854	0.785	0.807		0.984	***
Members aged 60 and above	0.244	0.272	0.231	***	0.218	
Number of observations	6626	2721	1801		2104	

Source: Own computation from 2010/11 Rwanda LTR Household Survey

Note: Stars indicated significance levels for t-tests of the equality of means for each of the variables between subsequent terciles (*significant at 10%; **significant at 5%; *** significant at 1%).

Table 2: Comparison of distance measures for different types of parcels in minutes

	Least cost path between parcels		Least cost path from home to [ ] parcels:		Own estimate of from home to [ ] parcels:	
	Mean	Sig	Mean	Sig	Mean	Sig
Panel A: By rental market participation						
Between households						
Participants (N = 1219, 1964, 1698)	17.23		11.608		15.865	***
Non-participants (N=1792, 1816, 1822)	18.14		10.416		11.88	
Within household (only participants)[a]						
Owner-cum-tenants						
All rented (N = 970, 1290, 1548)	20.76		16.303	***	22.498	***
Owned	19.09		10.086		12.265	
Owner-cum-fixed renter						
Fixed rented (N =700, 905, 1112)	21.6		17.397	***	24.573	***
Owned	18.88		9.732		12.821	
Owner-cum-free of charge renter						
Free (N = 383, 546, 652)	18.2		13.371	**	18.47	***
Owned	18.64		10.389		11.749	
Panel B: By sales market participation						
Between households						
Participants (N=1496, 1799, 1816)	19.26		11.397	**	15.089	***
Non-participants	18.14		8.607		8.614	
Within household (only participants)[a]						
Purchased (N=878, 1315, 1469)	22.68	**	16.852	***	15.477	**
Other owned	17.26		11.128		17.605	

Source: Own computation from 2010/11 Rwanda LTR Household Survey.
N stands for number of households for each data columns in the same order; Sig refer to significance of difference between owned and the category under concern (*significant at 10%; **significant at 5%; *** significant at 1%). An empty "Sig" column implies difference is not significant at 10% or less.
[a] The least cost path for traded in (e.g., rented or purchased) refers to average distance from these parcels to owned parcels whereas for owned parcels it refers to average distance between owned parcels.

Table 3: Land fragmentation and incidence of crop shock: household level

	Fragmentation		Crop diversity	
	Simpson	**No. of parcels**	**Shannon**	**No. of crops**
Fragmentation-related measures				
Simpson land fragmentation index	-0.045**			
	(-2.376)			
Log of number of parcels		-0.026***		
		(-3.237)		
Shannon crop diversity measure			-0.021**	
			(-2.098)	
Log of number crops				-0.016
				(-1.535)
Coefficient of variation of parcel altitude	0.167	0.242	0.118	0.122
	(0.891)	(1.269)	(0.634)	(0.651)
Average distance parcel- homestead (min)	-0.000	0.000	-0.000	-0.000
	(-0.150)	(0.182)	(-0.474)	(-0.395)
Parcel characteristics				
Log of total cropped area in hectares	-0.005	-0.002	-0.003	-0.003
	(-1.550)	(-0.690)	(-0.975)	(-0.762)
Soil type diversity index	0.018	0.019	0.011	0.010
	(0.882)	(0.953)	(0.554)	(0.529)
Parcel topography diversity index	0.007	0.007	-0.001	-0.002
	(0.336)	(0.329)	(-0.050)	(-0.082)
Household characteristics				
Age of household head	0.004**	0.004**	0.004**	0.004**
	(2.432)	(2.386)	(2.390)	(2.396)
Age of household head squared	-0.000**	-0.000**	-0.000**	-0.000**
	(-2.173)	(-2.122)	(-2.060)	(-2.082)
Female headed household	0.012	0.012	0.014	0.014
	(1.304)	(1.306)	(1.467)	(1.462)
Head completed only primary school	0.007	0.008	0.006	0.006
	(0.822)	(0.908)	(0.732)	(0.729)
Head completed secondary education	0.006	0.007	0.004	0.004
	(0.393)	(0.469)	(0.266)	(0.264)
Members aged 14 and less	-0.003	-0.003	-0.003	-0.003
	(-1.118)	(-0.991)	(-1.098)	(-1.104)
Adult members 15 -35	-0.007**	-0.007**	-0.008**	-0.008**
	(-2.317)	(-2.173)	(-2.457)	(-2.443)
Adult members 35 - 60	-0.019**	-0.018**	-0.019**	-0.019**
	(-2.545)	(-2.445)	(-2.511)	(-2.522)
Members aged 60 and above	-0.019	-0.019	-0.020*	-0.019*
	(-1.598)	(-1.601)	(-1.675)	(-1.647)
Constant	0.119***	0.132***	0.126***	0.126***
	(2.719)	(3.001)	(2.853)	(2.778)
Number of observations	6,713	6,724	6,724	6,724
R-squared	0.007	0.007	0.006	0.006

Note: Absolute value of t-statics in parenthesis: *** significant at 1%; ** significant at 5%;* significant at 10%. Time varying village specific fixed effects are included, but not reported.

Table 4: Household level yield function

	(1)	(2)	(3)	(4)	(5)	(6)
Number of parcels	0.085***	0.070***	0.071***			
	(15.448)	(13.617)	(13.757)			
Simpson land fragmentation index				0.826***	0.595***	0.611***
				(13.784)	(9.963)	(10.216)
Shannon crop diversity measure		0.550***	0.533***		0.542***	0.522***
		(18.292)	(17.553)		(17.553)	(16.710)
Total cost distance in hours	0.031	0.008	0.008	0.102***	0.084***	0.084***
	(1.089)	(0.291)	(0.282)	(3.513)	(2.911)	(2.907)
Total cost distance squared	-0.005	-0.002	-0.001	-0.012**	-0.009	-0.009
	(0.965)	(0.273)	(0.243)	(1.991)	(1.513)	(1.484)
Hh has parcel outside the cell	-0.020	-0.020	-0.021	0.004	0.009	0.009
	(0.819)	(0.836)	(0.841)	(0.161)	(0.398)	(0.374)
Total cropped area (hectares, log)	-0.522***	-0.557***	-0.559***	-0.486***	-0.527***	-0.528***
	(45.448)	(48.483)	(49.169)	(43.958)	(47.115)	(47.735)
Share of rented in land	-0.013	0.048	0.063	-0.066	0.009	0.030
	(0.278)	(1.046)	(1.362)	(1.384)	(0.188)	(0.630)
Number of years parcel possessed	0.004***	0.003**	0.003***	0.005***	0.004***	0.004***
	(3.201)	(2.561)	(2.578)	(3.485)	(2.633)	(2.594)
Parcel located in wet land	0.148**	0.156**	0.157**	0.137**	0.152**	0.154**
	(2.215)	(2.458)	(2.474)	(2.003)	(2.340)	(2.369)
Irrigated land	0.042	0.083	0.089	0.028	0.072	0.079
	(0.665)	(1.420)	(1.521)	(0.458)	(1.241)	(1.364)
Good soil quality	0.160***	0.158***	0.157***	0.184***	0.177***	0.175***
	(4.974)	(5.134)	(5.115)	(5.680)	(5.701)	(5.655)
Medium soil quality	0.069*	0.066*	0.066*	0.070*	0.068*	0.068*
	(1.723)	(1.747)	(1.744)	(1.746)	(1.793)	(1.792)
Used knowledge from extension	0.178***	0.184***	0.192***	0.169***	0.176***	0.183***
	(3.849)	(4.054)	(4.262)	(3.626)	(3.851)	(4.042)
Experienced crop shock	-0.209***	-0.254***	-0.249***	-0.207***	-0.256***	-0.251***
	(6.529)	(8.262)	(8.140)	(6.441)	(8.291)	(8.131)
Age of household head	0.009	0.005	0.005	0.009*	0.006	0.006
	(1.576)	(0.982)	(0.962)	(1.707)	(1.139)	(1.123)
Age of household head squared	-0.000*	-0.000	-0.000	-0.000*	-0.000	-0.000
	(1.860)	(1.397)	(1.363)	(1.960)	(1.514)	(1.481)
Female headed household	-0.188***	-0.182***	-0.177***	-0.188***	-0.184***	-0.177***
	(6.167)	(6.261)	(6.055)	(6.211)	(6.343)	(6.093)
Head completed primary school	0.094***	0.074***	0.078***	0.093***	0.077***	0.080***
	(3.583)	(2.894)	(3.047)	(3.544)	(2.988)	(3.110)
Head completed secondary education	0.162***	0.124***	0.127***	0.182***	0.146***	0.146***
	(3.334)	(2.582)	(2.635)	(3.730)	(3.029)	(3.049)
Members aged 14 and less	0.027***	0.023***	0.023***	0.031***	0.027***	0.026***
	(3.161)	(2.805)	(2.742)	(3.616)	(3.239)	(3.180)
Adult members aged 15 to 35	0.021**	0.023**	0.023**	0.027**	0.028***	0.028***
	(2.012)	(2.202)	(2.205)	(2.539)	(2.733)	(2.750)
Adult members aged 35 to 60	0.016	0.011	0.014	0.026	0.020	0.023
	(0.695)	(0.506)	(0.647)	(1.138)	(0.911)	(1.040)
Members aged 60 and above	0.036	0.042	0.044	0.027	0.037	0.038
	(0.975)	(1.152)	(1.183)	(0.743)	(1.025)	(1.053)
Share of land with grains			0.062			0.021
			(0.268)			(0.092)
Share of land with tubers			0.252			0.194
			(1.086)			(0.860)
Share of land with tree crops			0.229			0.233
			(0.976)			(1.027)
Constant	4.104***	3.652***	3.508***	4.019***	3.614***	3.503***
	(30.465)	(27.169)	(13.547)	(29.933)	(27.092)	(13.727)
Number of observations	6,626	6,626	6,626	6,626	6,626	6,626
R^2	0.342	0.384	0.387	0.336	0.376	0.378

Note: Absolute value of t-statics in parenthesis: *** significant at 1%; ** significant at 5%;* significant at 10%. Time varying village specific fixed effects are included, but not reported.

Table 5: Results from frontier production function

	(1)	(2)	(3)	(4)
Production function				
Log of total cultivated area in hectares	0.291***	0.310***	0.289***	0.312***
	(29.446)	(31.479)	(29.270)	(31.445)
Log of total labor use in days	0.340***	0.348***	0.341***	0.355***
	(24.701)	(25.339)	(24.709)	(25.327)
Log of chemical fertilizer use in kg	0.096***	0.101***	0.091***	0.096***
	(5.382)	(5.526)	(5.104)	(5.320)
Log of pesticide use in kg	0.079***	0.076***	0.085***	0.082***
	(3.731)	(3.487)	(4.011)	(3.825)
Log of manure use in kg	0.119***	0.117***	0.117***	0.118***
	(12.888)	(12.525)	(12.684)	(12.707)
Dummy zero chemical fertilizer use	0.075	0.082	0.064	0.061
	(1.436)	(1.536)	(1.219)	(1.156)
Dummy zero pesticide use	-0.135***	-0.151***	-0.160***	-0.173***
	(3.259)	(3.557)	(3.793)	(4.070)
Dummy zero manure use	0.526***	0.509***	0.515***	0.516***
	(8.861)	(8.583)	(8.674)	(8.668)
Share of rented in land	-0.002	-0.015	0.019	-0.003
	(0.050)	(0.391)	(0.509)	(0.073)
Number of years parcel possessed	0.004***	0.003***	0.003***	0.004***
	(3.534)	(3.058)	(3.401)	(3.416)
Parcel located in wet land	0.105**	0.095*	0.116**	0.116**
	(2.110)	(1.917)	(2.327)	(2.324)
Irrigated land	0.029	0.037	0.036	0.037
	(0.564)	(0.715)	(0.691)	(0.712)
Good soil quality	0.123***	0.133***	0.120***	0.129***
	(4.648)	(5.018)	(4.518)	(4.835)
Medium soil quality	0.082**	0.085**	0.083**	0.092***
	(2.350)	(2.421)	(2.363)	(2.620)
Used improved seed	0.029	-1.231**	0.034	0.091
	(0.313)	(2.451)	(0.360)	(1.044)
Use knowledge from extension services	-0.006	0.065	-0.004	-0.010
	(0.061)	(0.498)	(0.040)	(0.106)
Experienced crop shock	-0.133*	-0.197	-0.125	-0.198***
	(1.722)	(1.375)	(1.559)	(2.779)
Household has parcel outside the cell	0.022	-0.015	0.021	-0.019
	(1.055)	(0.740)	(1.002)	(0.929)
Time dummy	-0.084***	-0.077***	-0.082***	-0.077***
	(4.344)	(3.948)	(4.238)	(4.002)
Share of land with grains			0.498***	0.471***
			(3.147)	(2.932)
Share of land with tubers			0.566***	0.532***
			(3.551)	(3.302)
Share of land with tree crops			0.670***	0.665***
			(4.177)	(4.098)
Constant	3.369***	4.028***	2.862***	2.783***
	(16.741)	(7.951)	(11.704)	(11.391)
Inefficiency parameters				
Number of parcels	-0.135***		-0.133***	
	(4.780)		(4.798)	
Simpson land fragmentation index		-0.446***		-0.917***
		(8.070)		(3.450)
Shannon crop diversity measure	-0.350***	-0.223***	-0.328***	-0.429***
	(5.917)	(7.885)	(5.884)	(3.945)
Total cost distance in hours	0.034	-0.045*	0.031	-0.120*
	(0.701)	(1.724)	(0.664)	(1.785)
Total cost distance squared in hours	-0.001	0.006	-0.001	0.015
	(0.065)	(1.231)	(0.073)	(1.264)
Used improved seed	0.062	-1.342**	0.051	0.189
	(0.404)	(2.564)	(0.331)	(1.014)

Use knowledge from extension services	-0.077	0.059	-0.073	-0.080
	(0.455)	(0.349)	(0.429)	(0.376)
Crop shock	0.216*	0.075	0.216*	0.161
	(1.923)	(0.493)	(1.897)	(1.163)
Age of household head	0.002	0.001	0.002	0.004*
	(1.478)	(0.723)	(1.476)	(1.825)
Female headed household	0.108***	0.094***	0.100***	0.125**
	(2.741)	(3.827)	(2.601)	(2.269)
Head completed only primary school	-0.093**	-0.071***	-0.096**	-0.127**
	(2.382)	(2.982)	(2.505)	(2.276)
Head completed secondary education	-0.188**	-0.125***	-0.183**	-0.235*
	(1.996)	(2.723)	(2.015)	(1.811)
Constant	1.141***	1.688***	1.136***	0.859***
	(10.425)	(3.587)	(10.486)	(4.781)
No of observations	6,624	6,624	6,624	6,624
Log-Likelihood (LL)	-7,393.69	-7,430.11	-7,380.68	-7,411.19
χ^2	6,821.105	7,479.988	6,861.742	7,565.529
σ_u	0.469	0.103	0.461	0.562
σ_v	0.657	0.736	0.656	0.653
LL for H_0: $\sigma_u = 0$	-7,561.226	-7,561.226	-7,546.216	-7,546.216
χ^2_c	335.066	262.230	331.064	270.043

Note: Absolute value of t-statics in parenthesis: *** significant at 1%; ** significant at 5%;* significant at 10%. Village specific fixed effects are included, but not reported.

Appendix table 1: Household level yield function – restricted sample

	(1)	(2)	(3)	(4)	(5)	(6)
Number of parcels	0.105***	0.085***	0.087***			
	(12.708)	(10.657)	(10.828)			
Simpson land fragmentation index				0.782***	0.567***	0.590***
				(10.663)	(7.776)	(7.938)
Shannon crop diversity measure		0.586***	0.563***		0.593***	0.566***
		(15.379)	(14.518)		(15.231)	(14.262)
Total cost distance in hours	0.017	-0.013	-0.012	0.103***	0.071*	0.072*
	(0.440)	(0.341)	(0.304)	(2.625)	(1.887)	(1.910)
Total cost distance squared	-0.003	0.002	0.002	-0.009	-0.004	-0.005
	(0.425)	(0.345)	(0.313)	(1.230)	(0.612)	(0.623)
Total cropped area (hectares, log)	-0.525***	-0.569***	-0.570***	-0.488***	-0.539***	-0.539***
	(35.081)	(37.846)	(38.122)	(32.852)	(35.819)	(36.008)
Share of rented in land	0.010	0.069	0.079	-0.057	0.022	0.036
	(0.163)	(1.172)	(1.319)	(0.910)	(0.370)	(0.584)
Number of years parcel possessed	0.003*	0.002	0.003	0.004**	0.002	0.003
	(1.931)	(1.447)	(1.524)	(2.120)	(1.483)	(1.543)
Parcel located in wet land	0.056	0.078	0.069	0.029	0.059	0.050
	(0.675)	(0.962)	(0.854)	(0.342)	(0.717)	(0.618)
Irrigated land	0.137*	0.156**	0.161**	0.102	0.129*	0.136*
	(1.697)	(2.095)	(2.174)	(1.255)	(1.721)	(1.805)
Good soil quality	0.155***	0.160***	0.156***	0.167***	0.168***	0.164***
	(3.710)	(3.968)	(3.880)	(3.966)	(4.152)	(4.061)
Medium soil quality	-0.009	-0.012	-0.012	-0.008	-0.010	-0.010
	(0.169)	(0.239)	(0.256)	(0.160)	(0.199)	(0.212)
Used knowledge from extension	0.158***	0.162***	0.166***	0.148**	0.153***	0.156***
	(2.706)	(2.819)	(2.915)	(2.507)	(2.655)	(2.727)
Experienced crop shock	-0.181***	-0.225***	-0.222***	-0.185***	-0.233***	-0.228***
	(4.186)	(5.448)	(5.409)	(4.263)	(5.582)	(5.511)
Age of household head	0.016**	0.010	0.010	0.014**	0.009	0.009
	(2.154)	(1.443)	(1.433)	(1.963)	(1.320)	(1.304)
Age of household head squared	-0.000**	-0.000*	-0.000*	-0.000**	-0.000*	-0.000
	(2.251)	(1.731)	(1.709)	(2.139)	(1.662)	(1.636)
Female headed household	-0.222***	-0.207***	-0.202***	-0.219***	-0.206***	-0.201***
	(5.891)	(5.821)	(5.680)	(5.714)	(5.717)	(5.523)
Head completed primary school	0.070**	0.048	0.050	0.072**	0.050	0.051
	(2.017)	(1.438)	(1.479)	(2.073)	(1.520)	(1.532)
Head completed secondary education	0.192***	0.165**	0.165**	0.212***	0.183***	0.180***
	(2.728)	(2.430)	(2.420)	(2.987)	(2.673)	(2.622)
Members aged 14 and less	0.023**	0.021*	0.020*	0.026**	0.023**	0.022**
	(1.964)	(1.813)	(1.769)	(2.175)	(2.014)	(1.974)
Adult members aged 15 to 35	-0.000	-0.000	-0.000	-0.003	-0.002	-0.002
	(0.017)	(0.025)	(0.009)	(0.220)	(0.154)	(0.126)
Adult members aged 35 to 60	-0.040	-0.032	-0.030	-0.024	-0.020	-0.019
	(1.274)	(1.067)	(1.010)	(0.766)	(0.653)	(0.608)
Members aged 60 and above	0.010	0.020	0.020	0.014	0.025	0.024
	(0.183)	(0.397)	(0.389)	(0.274)	(0.489)	(0.472)
Share of land with grains			-0.259			-0.293
			(0.856)			(0.990)
Share of land with tubers			-0.074			-0.125
			(0.242)			(0.417)
Share of land with tree crops			-0.105			-0.099
			(0.339)			(0.329)
Constant	3.966***	3.533***	3.720***	4.055***	3.613***	3.830***
	(21.816)	(20.631)	(10.829)	(22.431)	(21.151)	(11.328)
Number of observations	3,957	3,957	3,957	3,957	3,957	3,957
R^2	0.356	0.403	0.405	0.346	0.393	0.395

Note: Absolute value of t-statics in parenthesis: *** significant at 1%; ** significant at 5%;* significant at 10%. Time varying village specific fixed effects are included, but not reported.

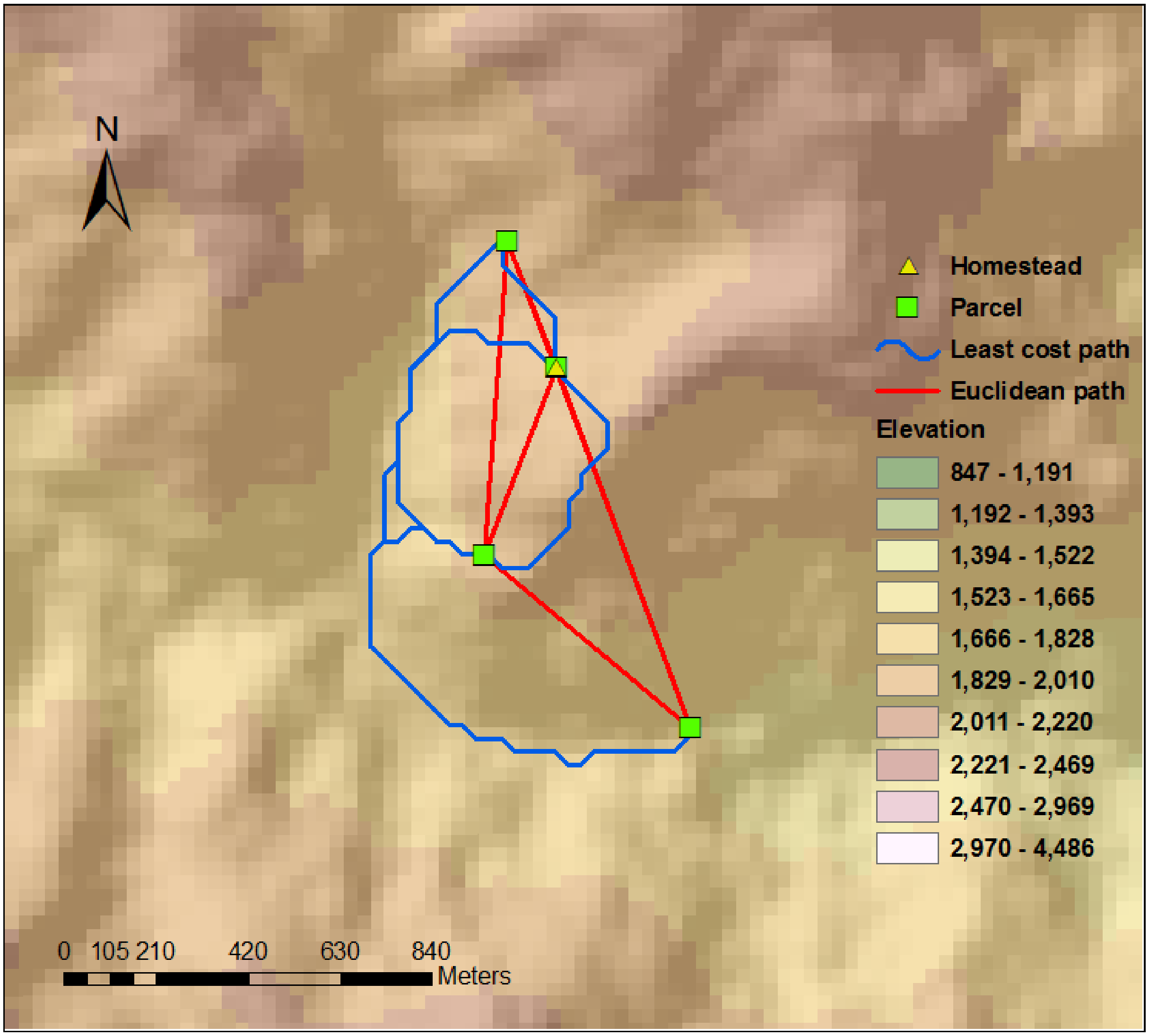


Figure 1: Pair-wise least cost path including the homestead parcel

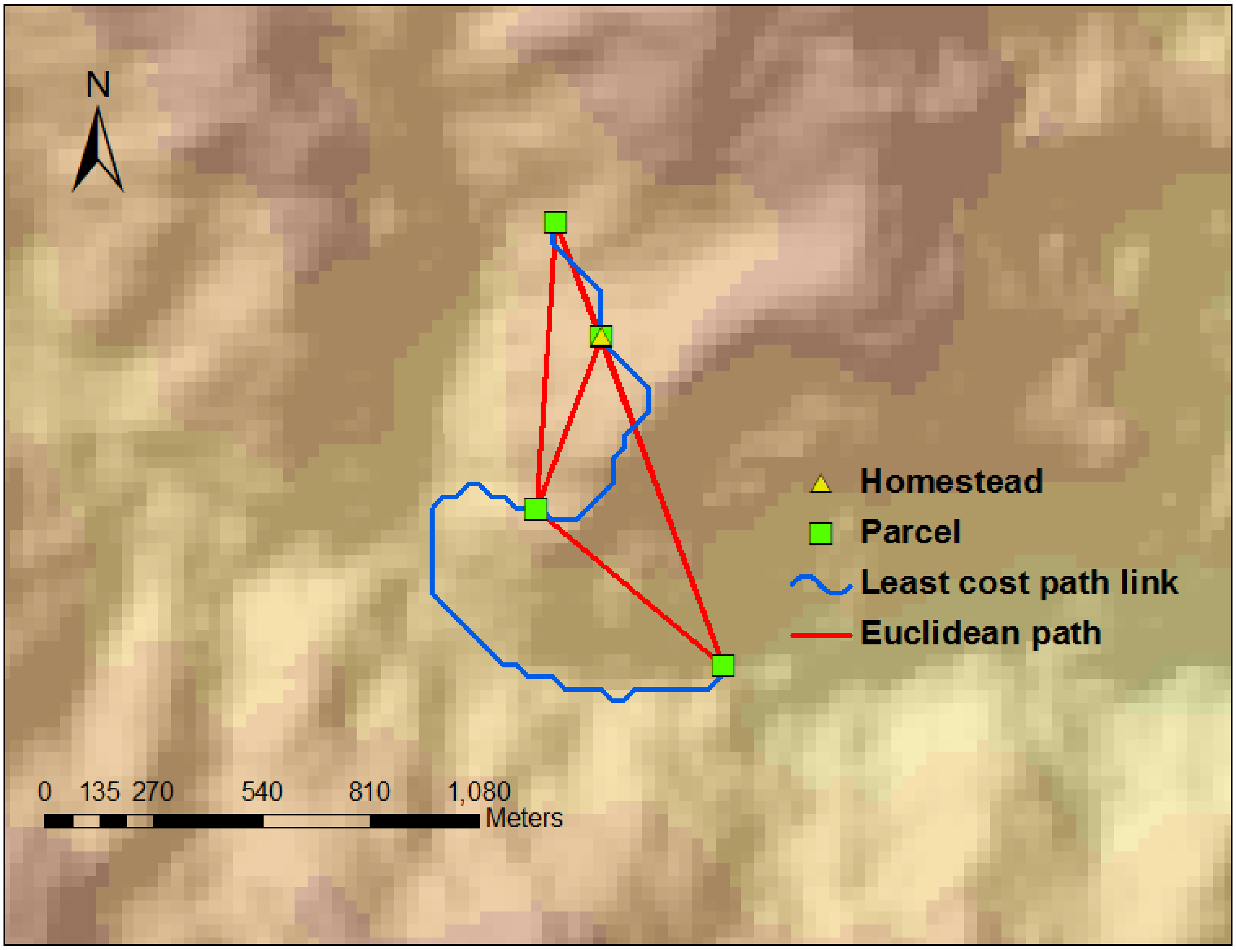


Figure 2: Least cost path link starting and ending at the homestead parcel

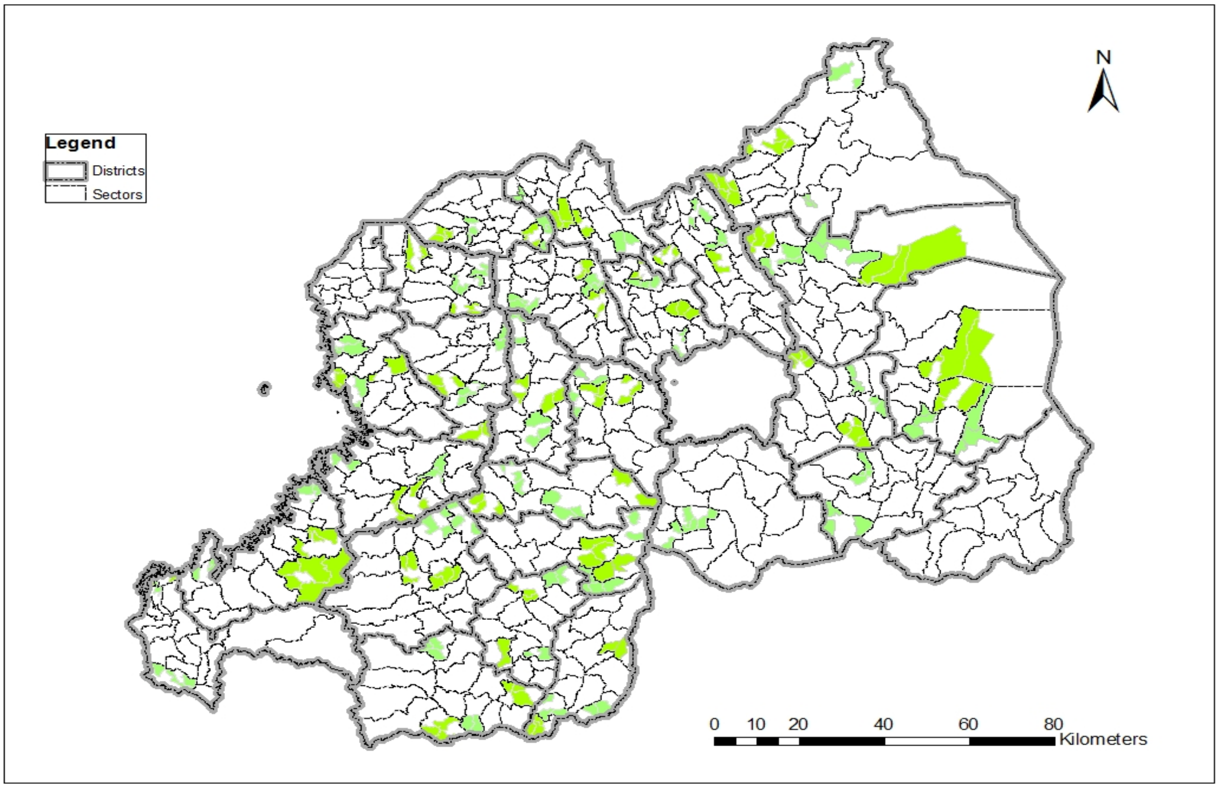
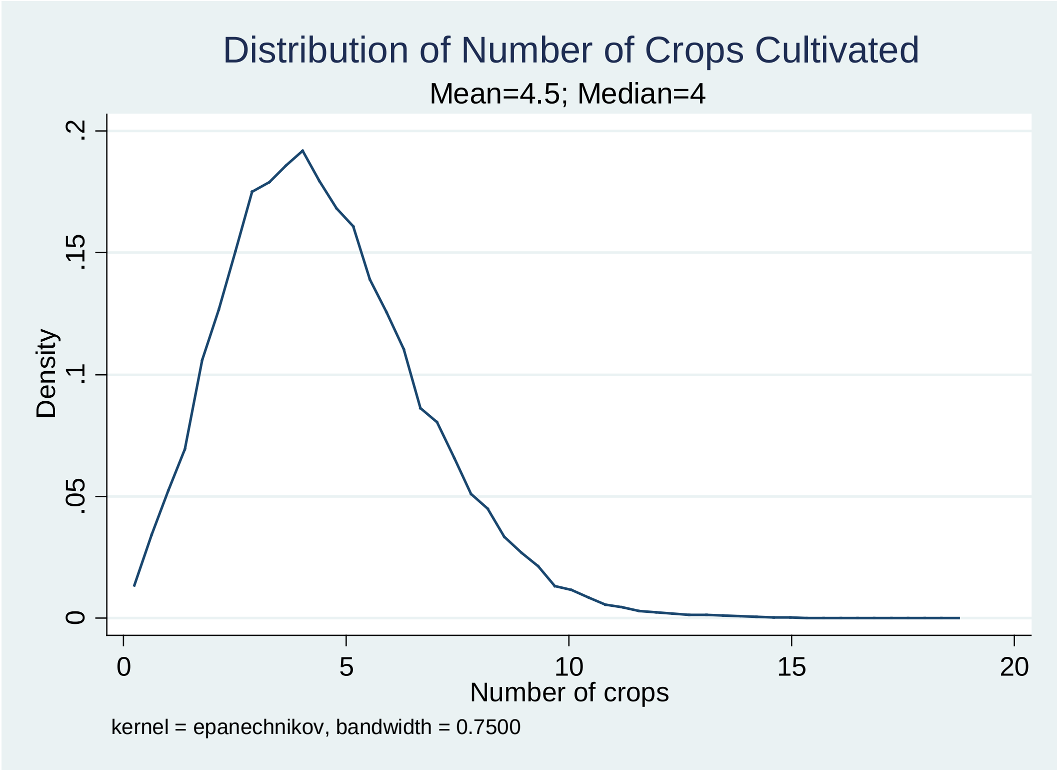
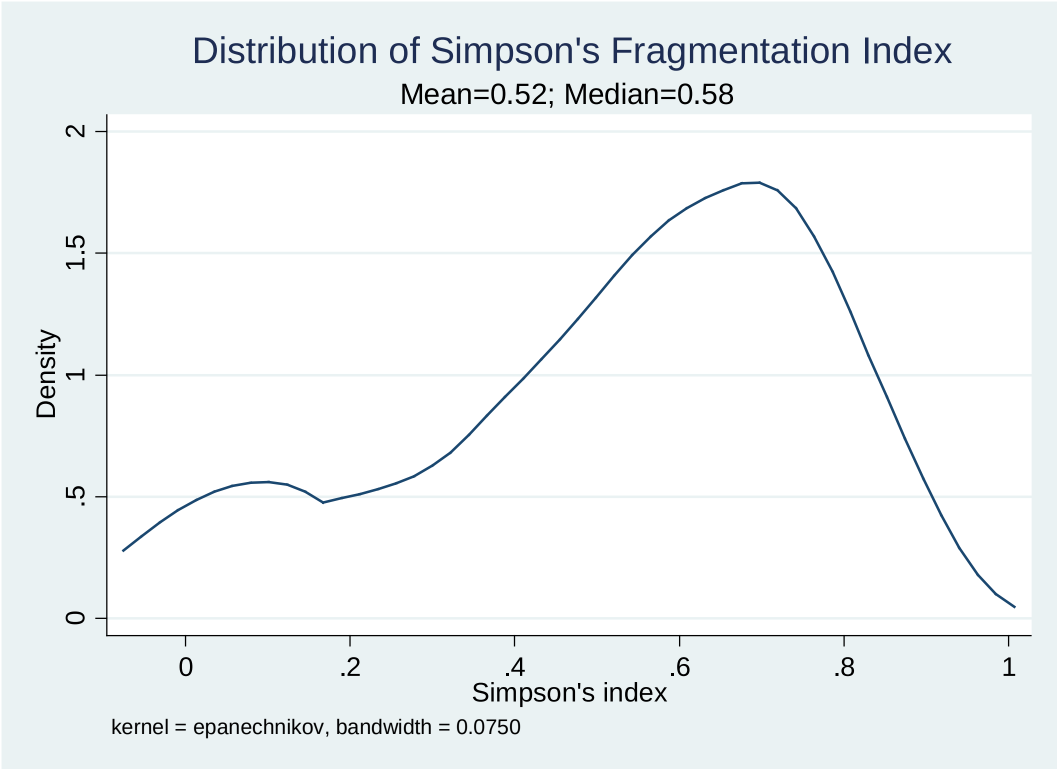


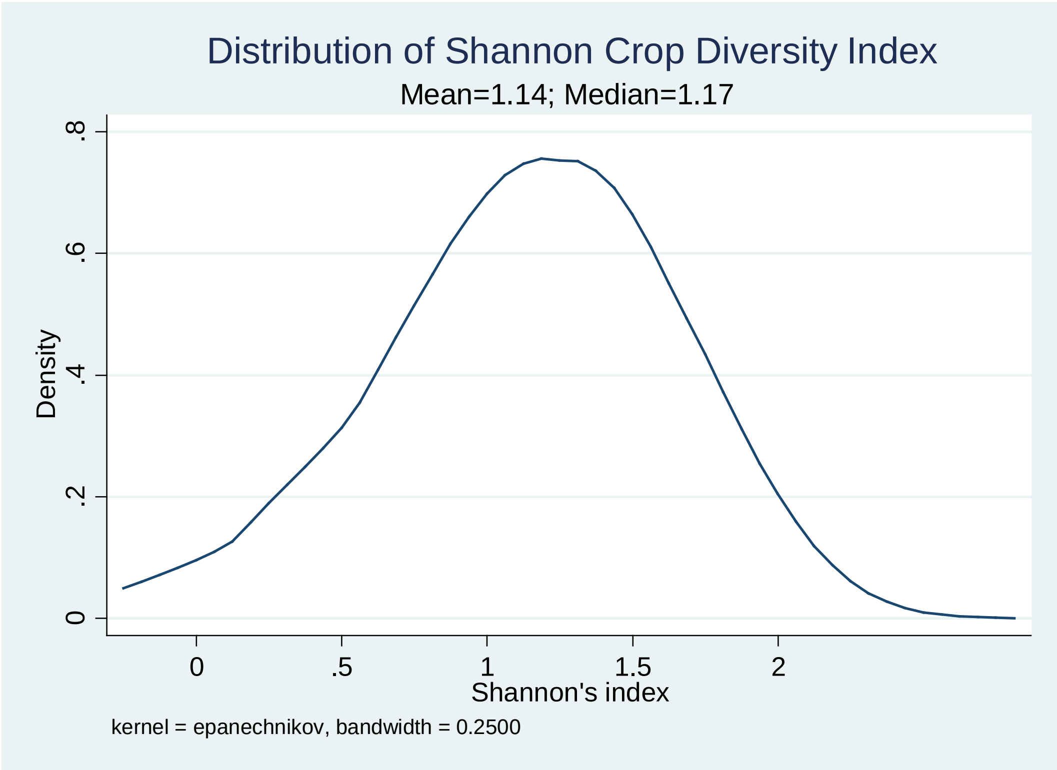
Figure 3: Map of sampled cells (300 villages, 3,600 households)



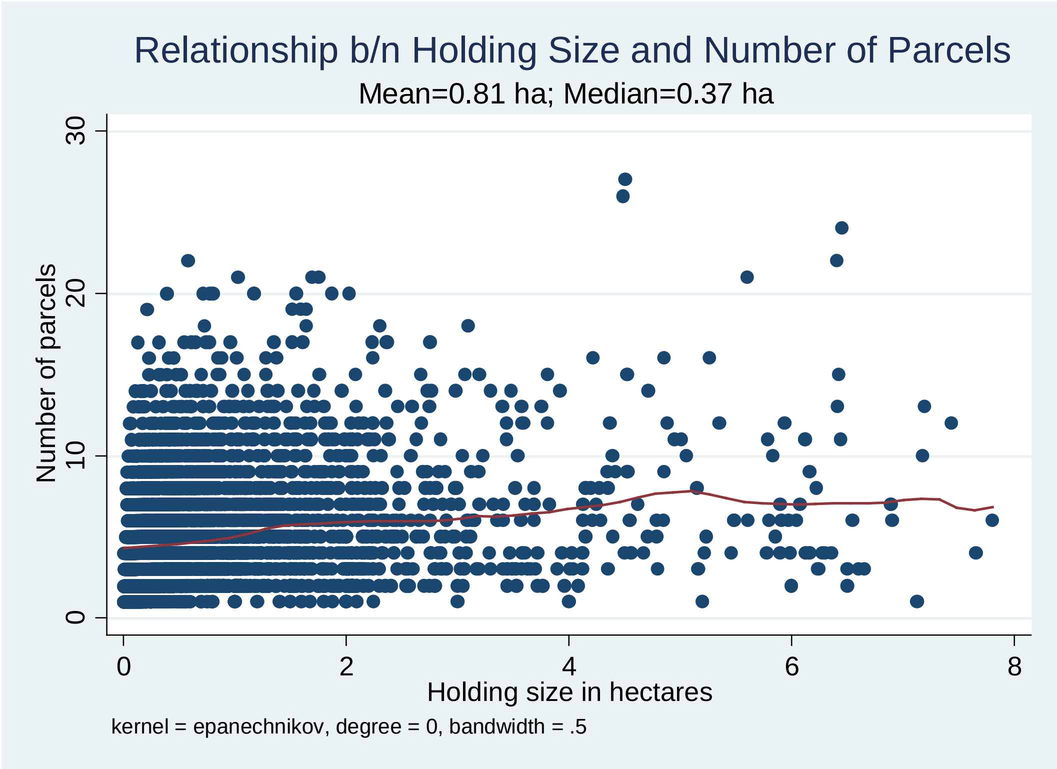
Appendix figure 1: Distribution of number of crops cultivated



Appendix figure 2: Distribution of Simpson's fragmentation index



Appendix figure 3: Distribution of Shannon crop diversity index



Appendix figure 4: Relationship of holding size and number of parcels

References

Ali, D. A. and K. Deininger. 2013. "Is There a Farm Size-Productivty Relationship in African Agriculture? Evidence from Rwanda." *Land Economics*, *forthcoming*.

Andre, C. and J. P. Platteau. 1998. "Land Relations under Unbearable Stress: Rwanda Caught in the Malthusian Trap." *Journal of Economic Behavior and Organization*, ***34***(1), 1-47.

Baker, M. and T. J. Miceli. 2005. "Land Inheritance Rules: Theory and Cross-Cultural Analysis." *Journal of Economic Behavior and Organization*, ***56***(1), 77-102.

Battese, G. E. 1997. "A Note on the Estimation of Cobb-Douglas Production Functions When Some Explanatory Variables Have Zero Values." *Journal of Agricultural Economics*, ***48***(2), 250-252.

Bentley, J. 1987. "Economic and Ecological Approaches to Land Fragmentation: In Defense of a Much Maligned Phenomenon." *Annual Review of Anthropology*, ***16***(1), 31-67.

Blarel, B., P. Hazell, F. Place and J. Quiggin. 1992. "The Economics of Farm Fragmentation: Evidence from Ghana and Rwanda." *World Bank Economic Review*, ***6***(2), 233-254.

Chen, Z., W. E. Huffman and S. Rozelle. 2009. "Farm Technology and Technical Efficiency: Evidence from Four Regions in China." *China Economic Review*, ***20***(2), 153-161.

Coelli, T., S. Perelman and E. Romano. 1999. "Accounting for Environmental Influences in Stochastic Frontier Models: With Application to International Airlines." *Journal of Productivity Analysis*, ***11***(3), 251-273.

Deininger, K., G. Carletto and S. Savastano. 2012. "Land Fragmentation, Corpland Abandonment, and Land Market Operation in Albania." *World Development*, ***40***(10), 2108-2122.

Di Falco, S., I. Penov, A. Aleksiev and T. M. van Rensburg. 2010. "Agrobiodiversity, Farm Profits and Land Fragmentation: Evidence from Bulgaria." *Land Use Policy*, ***27***, 763-771.

Fenoaltea, S. 1976. "Risk, Transaction Costs, and the Organization of Medieval Agriculture." *Explorations in Economic History*, ***13***(2), 129-151.

Foster, A. and M. R. Rosenzweig. 2010. "Barriers to Farm Profitability in India: Mechanization, Scale, and Credit Markets." University of Pennsylvania Working Paper, Philadelphia.

Heston, A. and D. Kumar. 1983. "The Persistence of Land Fragmentation in Peasant Agriculture: An Analysis of South Asian Cases." *Explorations in Economic History*, ***20***(2), 199-220.

Hung, P. V., T. G. MacAulay and S. P. Marsh. 2007. "The Economics of Land Fragmentation in the North of Vietnam." *Australian Journal of Agricultural and Resource Economics*, ***51***(2), 195-211.

Kawasaki, K. 2010. "The Costs and Benefits of Land Fragmentation of Rice Farms in Japan." *Australian Journal of Agricultural and Resource Economics*, ***54***(509), 526.

Kumbhakar, S. C., S. Ghosh and J. T. McGuckin. 1991. "A Generalized Production Frontier Approach for Estimating Determinants of Inefficiency in U.S. Dairy Farms." *Journal of Business and Economic Statistics*, ***9***(3), 279-286.

McCloskey, D. N. 1975. *The Persistence of English Common Fields.* Princeton University Press, Princeton, N.J.

Platteau, J. P. and J.-M. Baland. 2001. "Impartial Inheritance Versus Equal Division: A Comparative Perspective Centered on Europe and Sub-Saharan Africa." in A. de Janvry, et al. (eds.), *Access to Land Rural Poverty and Public Action*, Oxford University Press, Oxford.

Rahman, S. and M. Rahman. 2008. "Impat of Land Fragmentation and Resource Ownership on Productivity and Efficiency: The Case of Rice Producers in Bangladesh." *Land Use Policy*, ***26***(1), 95-103.

Republic of Rwanda. 2004. "National Land Policy." Kigali.

Republic of Rwanda. 2009. "Strategic Plan for the Transformation of Agriculture in Rwanda Phase II (Psta II). Final Report." Kigali.

Sengupta, N. 2006. "Fragmented Landholding, Productivity, and Resilience Management." *Environment and Development Economics*, ***11***(4), 507-532.

Sherlund, S. M., C. B. Barrett and A. A. Adesina. 2002. "Smallholder Technical Efficiency Controlling for Environmental Production Conditions." *Journal of Development Economics*, ***69***(1), 85-101.

Simons, S. 1987. "Land Fragmentation and Consolidation: A Theoretical Model of Land Configuration with an Empirical Analysis of Fragmentation in Thailand." *Ph.D.thesis, University of Maryland, College Park*.

Tan, S. H., N. Heerink, G. Kruseman and F. T. Qu. 2008. "Do Fragmented Landholdings Have Higher Production Costs? Evidence from Rice Farmers in Northeastern Jiangxi Province, Pr China." *China Economic Review*, ***19***(3), 347-358.

Tanaka, T. 2007. "Resource Allocation with Spatial Externalities: Experiments on Land Consolidation." *B.E.Journals in Economic Analysis and Policy: Topics in Economic Analysis and Policy*, ***7***(1), 1-31.

Tobler, W. 1993. "Three presentations on geographical analysis and modeling: Non-isotropic geographic modeling speculations on the geometry of geography global spatial analysis." *Technical Report, 93,* National center for geographic information and analysis.

Wan, G. H. and E. Cheng. 2001. "Effects of Land Fragmentation and Returns to Scale in the Chinese Farming Sector." *Applied Economics*, ***33***(2), 183-194.

Wu, Z., M. Liu and J. Davis. 2005. "Land Consolidation and Productivity in Chinese Household Crop Production." *China Economic Review*, ***16***(1), 28-49.