A spatial model of household fuelwood extraction in northern Uganda

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Abstract

Previous studies have suggested that market failures are household-specific and not commodity-specific (de Janvry et al, 1991); transaction costs determine whether a household is a buyer, seller or self-sufficient for a given good and how much it is going to produce (Key et al, 2000). Focusing on fuelwood production in northern Uganda, this paper extends previous studies by introducing fixed transaction costs associated with reaching the market *and* the forest. We predict that households sort in space, with autarkic households being located closest to the forest and farthest from the market, buyer households located closest to the market and farthest from the forest and seller households located at intermediate distances from the market and forest. We show that the spatial predictions hold in partial and general equilibrium settings. We test the predictions of our model using data from northern Uganda and find evidence that supports the predictions from our theoretical model. The ensuing spatial-dynamic simulations based on the static allow us to make forecasts of where forest degradation is likely to occur as well as to model spillover effects resulting from the introduction of a conservation intervention like a protected area.

Keywords: spatial household model, household sorting, transaction costs, fuelwood extraction, forest degradation

Introduction

In the bio-economic field recent studies have modeled changes in the landscape along two dimensions: time *and* space. These studies posit that the optimal shadow price of biomass varies over space and time (Smith, Sanchirico et al. 2009). Depending on the proximity of the households to the forest resources, some patches are going to be more heavily exploited than others (López-Feldman and Wilen 2008; Smith, Sanchirico et al. 2009). For conservation policy, it matters which patches become degraded. Therefore, given the area and connectivity requirements of many natural systems (e.g. importance for meta-population dynamics), ignoring the spatial aspect of the problem can lead to biased and inconsistent estimators and, in more practical terms, to ineffective and detrimental conservation and poverty alleviation policies (Pattanayak and Butry 2005; Alix-Garcia 2007; López-Feldman and Wilen 2008).

This paper develops a static model for fuelwood extraction as a function of the households' location with respect to markets and forests as well as the forest quality. As previous studies have suggested, market failures are household- rather than commodity-specific, with the household location and socio-economic characteristics being the determinants of whether or not the household will participate in the market (de Janvry, Fafchamps et al. 1991; Key, Sadoulet et al. 2000). Whether or not a household participates in the market as a buyer or a seller depends on the household's location with respect to the market and the transaction costs it incurs. The lack of infrastructure and limited information increase the transaction costs (de Janvry, Fafchamps et al. 1991; Key, Sadoulet et al. 2000). Similarly, the household's decision whether or not to produce a commodity like fuelwood depends on the household location relative to the forest and the forest quality at the site (e.g., Robinson, Williams et al. 2002; Pattanayak, Sills et al. 2004). If the distance to the forest is too great or the forest has been significantly degraded, it may be optimal for the household to purchase fuelwood from the market rather than to collect it. In sum, the extractive behavior of a household is determined by both proportional transaction costs (e.g. search costs) associated with the forest quality, which determines the ease of harvesting fuelwood, and fixed transaction costs associated with travelling to the market and to the forest. We predict that households sort in space, with the autarkic households being closest to the forest, the buyer households-closest to the market and the seller households located at intermediate distances from the forest and the market, *ceteris paribus.* Differences in the households' income and education affect the critical distances that make households switch from one market participation regime to another (de Janvry & Sadoulet, 2006).

In this chapter we extend the static household production model in Key et al (2000) to fuelwood collection in a developing country. We add to previous studies considering transaction costs as determinants of household fuelwood collection behavior (e.g., Fafchamps & Hill, 2004; Robinson et al, 2002; Pattanayak, Sills et al. 2004; Kohlin & Parks, 2001; MacDonald et al, 2001 and the review by Albers & Robinson, 2012) by explicitly modeling the role of household-specific location with respect to both markets and forests. We allow households to be scattered in space; whether and how much fuelwood a household will collect is determined by the presence of both proportional and fixed tranaction costs. Similar to MacDonald et al (2001), we treat space comprised of discrete forest patchs which may or may not be adjacent to each other.

The presence of fixed transaction costs introduces discontinuities in the model: the household has to choose the market participation regime that yields the highest utility and, conditional on that, how much fuelwood, if any, to produce. In other words, here we consider fuelwood collection on both the intensive and extensive margins. Previous studies have tended to focus on the intensive margin (how much fuelwood to collect as a function of the proximity to the forest or which patch to collect fuelwood from), without considering that at some point it may be optimal for the household to buy fuelwood than to produce it or sell fuelwood (Albers & Robinson, 2012). Here we explicitly consider the role of location in determining the market participation regime of the household. Using the predictions of the static model and cross-sectional spatially-explicit survey data collected in northern Uganda in 2009, we test hypotheses about the importance of the household location in space. We find statistically significant spatial patterns in accordance with the predictions from our model: (1) buyers tend to be located in cities away from forest patches; (2) sellers are at intermediate distances between forests and markets; they collect more fuelwood than self-sufficient households; (3) autarkic households are located farthest from markets and close to cities. To our knowledge, no prior study in the development literature has addressed a similar issue of households sorting in space by market participation regime, determined by location.

Another contribution of this paper to the literature is that here we examine the role of partial vs. general equilibrium assumptions. In other words, we compare the model predictions when we allow the prices of fuelwood at a market to be determined by the number of participating households in that time period. We find that under general equilibrium the critical distances for switching between one market participation regime to another are changed in favor of creating more self-sufficient households; otherwise, the qualitative predictions of the model with regards to the sorting of households across space remain unchanged. By examining the spatial patterns of sellers and buyers in our sample, we conclude that partial equilibrium is a reasonable assumption for our data. Even though many studies consider the implications of incomplete markets in the household production framework, to our knowledge only one prior study (Robinson et al, 2002) considers changes in predictions of their theoretical model when general equilibrium is imposed. [1]

The remainder of this paper is divided into 6 sections. Section I.1 develops the household fuelwood production model with proportional and fixed transaction costs and makes predictions about the spatial distributions of the buyers, sellers and self-sufficient households under partial equilibrium. Section I.2 extends the model to the general equilibrium case. Section I.3 presents the assumptions behind the theoretical model and estimation approaches and Section I.4 presents the estimation techniques and data used for the empirical analysis. Section I.5 presents the results and the last section concludes.

The static household production model with transaction costs under partial equilibrium

The model presented in this paper uses the household production framework from the development economics literature (see Singh et al, 1986; Singh, Strauss and Squire, 1986; de Janvry & Sadoulet, 2006 for reviews). The household production models

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[1] Although the study also examines the role of the proximity to markets, it differs from ours in several important ways: (1) space is represented as a continuum, with villagers clustered in the same location; in contrast, our paper allows for forest patches and households to be scattered in space; (2) households are allowed to go to buy *and* produce fuelwood *at the same time;* in contrast, in our model, travelling to the market and the forest imposes costs, so a utility maximizing household will choose either being a buyer or being a producer; (3) the opportunity cost of time is exogenous and fixed; in our model we allow to vary depending on the household characteristics and the price of the agricultural commodity.

incorporate the three roles of the household: the household as a consumer, the household as a producer and the household as the supplier of labor. The producer, consumer and labor supply decisions are interdependent. In truly subsistent households these decisions are made simultaneously as a household can consume only what it produces and must rely on own labor (Singh et al, 1986). In contrast, if a household is a price taker in all commodity markets (or faces a virtual price for a commodity it consumes but does not produce and vice versa), the optimal household production can be determined independently of consumption and leisure. Thus, the optima can be found recursively: in the first stage the household maximizes its profit from the production function, the values from which can be used for the maximization of utility. This implies that the farm technology, prices of inputs and outputs and the quantities of fixed inputs affect consumption decisions, but the household preferences, income and the prices of consumption commodities do not affect the production function. The household production model in this chapter allows households to switch from being autarkic (self-sufficient) to buyers or sellers in the market and vice versa depending on the transaction costs.

As in any other sub-Saharan African countries, many rural households in northern Uganda depend on fuelwood collection for part of their subsistence. These activities are significant drivers for forest degradation and, in certain cases, for deforestation and hence pose a severe threat to habitats and ecosystems in the area (Angelsen and Kaimowitz 1999). The more fuelwood households in a village collect from a given forest patch, the greater the forest degradation and the higher the transaction costs associated with searching for fuelwood in a forest patch. The state of the forest imposes transaction (search) costs, t_{pc}, which are a function of the state of the forest, S, and are proportional to the amount of fuelwood collected. In this case, the presence of the proportional transaction costs in essence lowers the price sellers obtain per unit of fuelwood sold on the market. Additionally, a household faces fixed transaction costs associated with going to the market, t_{fc}^{m} and to the forest, t_{fc}^{f}. These are lump-sum costs that do not vary with the amount of fuelwood collected or sold on the market; instead, they are a function of the observed distance to the market, d^m, and the distance to the forest, d^f, in each period.

As pointed out by Key et al. (2000), the presence of fixed transaction costs creates discontinuities in the Lagrangian function used to derive the first order conditions in the traditional household production model. For this reason, in the presence of fixed transaction costs the optimal solution is found in two stages: the first stage obtains the optimal levels of consumption and production conditional on market participation, whereas the second stage derives the conditions for market participation and autarky (Key, Sadoulet et al. 2000). The first stage household utility maximization problem and its first order conditions (FOC) are presented below. The variable descriptions are presented in Table 1.

Table 1: Parameters in the household production model. Throughout the paper, goods (fuelwood or a generic agricultural good are indexed by *i*, households-by *j* and forest patches-by *k*. The household subscripts have been suppressed in this table.

q_i	Amount of good i produced
c_i	Amount of good i consumed
m_i	Amount of good i bought/sold on the market, with $m_i>0$ indicating a sale and $m_i<0$ indicating a purchase of good I; $m_i=0$ indicates autarkic (self-sufficient households).
z	A vector of household characteristics
δ_i^m	1 of the household participated in a market exchange (i.e. went to the market) and 0 otherwise
δ_i^f	1 of the household collected fuelwood (went to the forest) and 0 otherwise
$t_{pc}(S_k)$	Proportional transaction costs associated with searching for fuelwood at patch k.
t_{fc}^m	Fixed transaction costs associated with reaching the market, varies by household
t_{fc}^f	Fixed transaction costs associated with reaching the forest patch, varies by household
d^m	Distance to the market from a household; varies by household
d^f	Distance to the forest patch; varies by household
S_m	Forest quality at a given patch m
x_i	Inputs (e.g. labor, capital)
T	Household endowment

The gist of the household production model is that households maximize utility given income and production constraints. The model assumes that households consume and produce only 2 commodities: fuelwood (indexed by subscript *fu*) and an agricultural good (indexed by subscript *ag*). Only households collecting fuelwood face proportional transaction costs; buyers on the market do not. Autarkic households incur fixed transaction costs associated with going to the forest. In addition to the proportional transaction costs associated with fuelwood extraction in a forest patch, sellers face fixed transactions costs associated with the distance to the market *and* the distance to the forest.

The generic household production model with transaction costs is given below. The vector x_i designates the inputs (labor, capital) used in the production functions. The model currently assumes that that land is not a decision variable in the model.

Deciding how much fuelwood to produce, conditional on a market participation regime

The household utility maximization problem, conditional on having chosen a market participation regime, is summarized below. The household maximizes the objective function, i.e. the household utility, represented by U(), by deciding on how much to produce, consume and trade on the market.

Model 1: Generic household production model with transaction costs for 2 commodities and partial equilibrium.

$$
\begin{aligned}
&Max_{c_i,q_i,m_i} U(c_i; z) \\
&s.t. \\
&(1)\ q_i - m_i = c_i \\
&(2)\ G(q_i, x_i; z_q) = 0 \\
&(3)\ \delta_i^m m_i \left(p_i - \delta^f t_{pc}(S)\right) + T - (\delta^f t^f_{fc} + \delta^m t^m_{fc}) = 0 \\
&(4)\ c_i, x_i, q_i \geq 0
\end{aligned}
$$

The first constraint specifies that a household cannot consume more than it produces or buys on the market (resource constraint). The second constraint is given by the production function for output q_i. The third constraint represents the cash constraint: it specifies that a household cannot spend more than it has.

The Lagrangian becomes

$$\Lambda = U(c_i; z) + \mu_i(q_i - m_i - c_i) + \phi_i G(q_i, x_i; z_q) + \psi(\delta_i^m m_i \left(p_i - \delta^f t_{pc}(S)\right) + T - (\delta^f t^f_{fc} + \delta^m t^m_{fc}))$$

As in Key et al (2000), the FOC of the generic model are given by

$$(1)\ \frac{\partial \Lambda}{\partial c_i} = \frac{\partial U}{\partial c_i} - \mu_i = 0$$

$$(2)\ \frac{\partial \Lambda}{\partial q_i} = \mu_i + \phi_i \frac{\partial G_i}{\partial q_i} = 0$$

$$(3)\ -\mu_i + \psi\left(\delta_i^m\left(p_i - \delta^f t_{pc}(S)\right)\right) = 0$$

The shadow price for fuelwood collection from (3) is given by

$$\tilde{p} = p_i - \delta^f t_{pc}(S) = \frac{\mu_i}{\psi}$$

Note, that it indirectly depends on the household characteristics.

The set of FOC allows us to implicitly derive a supply and a demand function for fuelwood. The particular expressions of the demand and supply equations are not possible without assuming a specific functional form for the utility and production functions. Still, the FOC imply that

$$\begin{aligned} q_{sji} &= f(p_i, S, p_x; z_q) \\ q_{dji} &= f(p_i, y_i; z_u) \end{aligned}$$

, where q_s is the quantity produced by household j and q_d is the quantity demanded by household *j* for good i. Under the assumption that fuelwood is a normal good, the quantity demanded increases with income, *y* (measured at the decision price). The amount of good *i* marketed by household *j*, m_{ij}, is the difference between the two, i.e. a function of p_i, S, p_x and dependent on the household characteristics z_q The FOC also suggest that the fuelwood supply will decrease with a lower environmental quality.

Deciding on a market participation regime

While the household production model from the previous section allows us to derive the optimal amount of fuelwood to be produced and consumed, conditional on market participation, the following analysis provides an analytical description of when a household is going to participate in the market either as a buyer or a seller. The household decision is based on comparing the indirect utilities from each choice (being autarkic, buying or selling on the market) (e.g. as in Key, Sadoulet et al. 2000).

The presence of fixed transaction costs delays the entry to the market, but once the household has reached the market, only the proportional transaction costs imposed by searching for fuelwood in a forest patch affect how much fuelwood the household is going to produce (Key et al, 2000; de Janvry et al, 1991, de Janvry & Sadoulet, 2006). The presence of proportional transaction costs modifies the prices buyers and sellers face in the market. Let the decision price a household faces be defined as

$$p_{fu}^{m*} = \begin{cases} \tilde{p} = \dfrac{\mu_{fu}}{\psi} \quad if \ m_{fu} = 0 \\ p_{fu}^{m} - t_{pc}(S) \ if \ m_{fu} < 0 \\ p_{fu}^{m} \quad if \ \ m_{fu} > 0 \end{cases} \text{for autarkic, seller and buyer households,}$$

respectively. Let y_0 be the income before any transaction costs are incurred. In other words, $y_0 = \sum_i p_i (q_i - x_i) + T$. A household buying fuelwood on the market has income $y = y_0 - t_{fc}^{m}$. A household selling fuelwood on the market has income

$y = y_0(p^m_{fu} - t_{pc}(S)) - (t^m_{fc} + t^f_{fc})$. Lastly, the income for an autarkic household is given by

$y = y_0\left(\tilde{p}\right) - t^f_{fc}$.

The indirect utilities for the buyer, seller and autarkic households are given by:

$$V^{buyer} = V(p^m_{fu}, y_0(p^m_{fu}) - t^m_{fc}; z)$$
$$V^{seller} = V(p^m_{fu} - t_{pc}(S), y_0(p^m_{fu} - t_{pc}(S)) - (t^m_{fc} + t^f_{fc}); z)$$
$$V^{autarky} = V(\tilde{p}, y_0(\tilde{p}) - t^f_{fc}; z) \qquad \text{(Equation 15)}$$

A comparison of the indirect utilities, which are a function of some critical distance to forest and the distance to market as well as prices, should indicate whether a household is autarkic, a buyer or a seller on the market. The next two subsections illustrate the sorting in more detail.

Sorting along prices

As Key et al (2000) demonstrated, households compare the indirect utilities from each type of market participation. The household indirect utility is increasing in prices for the sellers and decreasing in prices for the buyer households, while the indirect utility for the self-sufficient households is independent of the market price. The sorting of household indirect utilities as a function of the market price is given in Fig. 1 (this is also Fig. 1 from Key et al, 2000). As Key et al (2000) pointed out, the presence of fixed costs delays entry into the market for sellers and induces earlier exit from the market from buyers; graphically, these transaction costs represent discrete shifts of the indirect utility curves as shown in Fig. 1.

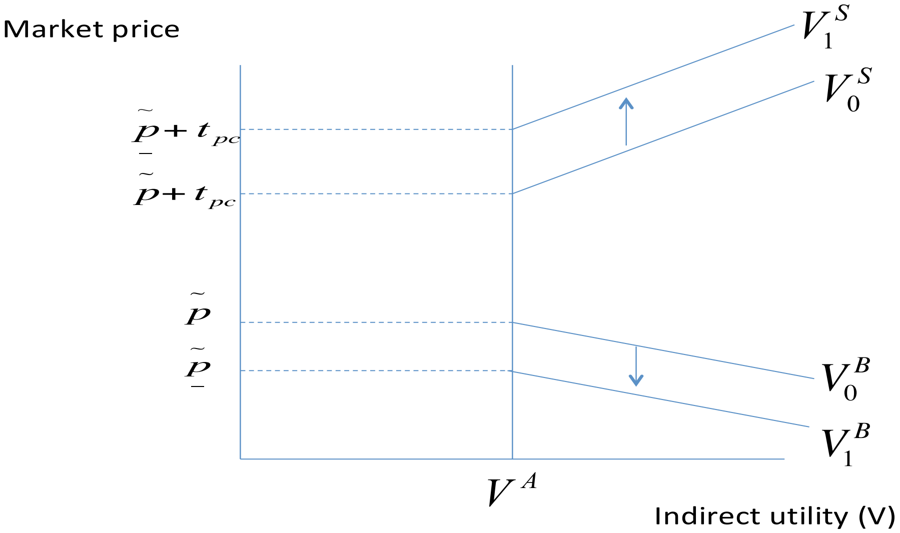

Figure 1: Households sorting according to market prices (figure modified from Fig.1 in Key et al, 2000). In contrast to Key et al (2000), in this paper we assume that buyers do not incur proportional transaction costs when they purchase fuelwood on the market. The household production model suggests that if the market price is sufficiently low, it may be optimal for households to purchase fuelwood on the market, *ceteris paribus*. When the price increases sufficiently, households switch to becoming self-sufficient or sellers of fuelwood. The presence of fixed transaction costs shifts the indirect utility curves, making the price range over which households remain self-sufficient larger (Key et al, 2000). This implies that fixed transaction costs like the distance to forests or markets increase, the region under autarky in the graph increases, *ceteris paribus*.

Sorting in space

The presence of fixed transaction costs implies discontinuities in the indirect utility function: depending on the household location with respect to the forest and the market, they choose whether to participate on the market as a buyer or a seller or become autarkic. In other words, the presence of fixed transaction costs implies a sorting pattern of households of space according to their proximity to the markets and the forest.

Lemma 1: The presence of transaction costs suggests a pattern of households sorting through space, with the autarkic households being closest to the forest and the buyer households being closest to the market and seller households located at intermediate distances (Fig. 2). The ordering in space holds true when the households are not aligned on a single line.

Proof

Let *dm* designate the household distance to market and *df*-the household distance to the forest. The presence of transaction costs lowers the income. For this reason, because the indirect function is increasing in income, the indirect utility function is decreasing in the fixed transaction costs. To maximize the indirect utility given certain prices for fuelwood, an autarkic household will choose the shortest distance to the forest; similarly, a buyer household will choose the distance closest to the market. Because both *df* and *dm* are included in the indirect function for sellers, the indirect utility will decrease going away from the market, but will increase approaching the forest. Given the tradeoff, the seller household will locate at intermediate distance from the forest and the market.

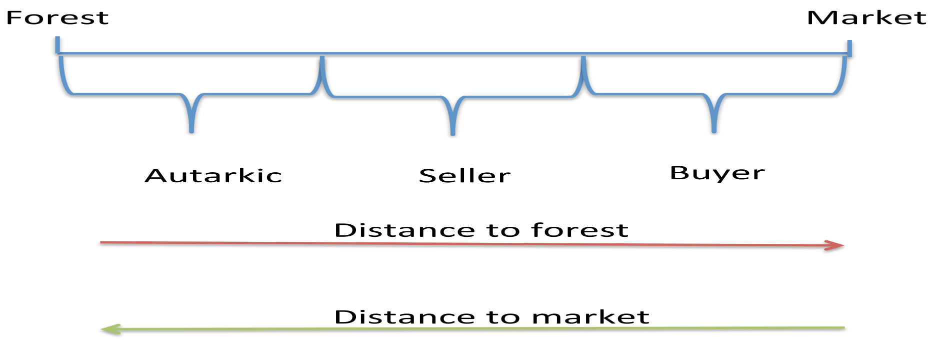

Figure 2: Sorting of households in space. The indirect utility is decreasing with the distance to the forest and the markets. This ordering in space holds for households not located on a single line.

The lemma suggests that for each household *j* there is a critical distance to the market, cm_j*, that makes household *j* indifferent between being a buyer and a seller on the market. Similarly, a critical distance to the forests, cff_j*, exists such that the household is indifferent between being sellers and being self-sufficient. An indirect expression for these distances can be obtained by equating the indirect utilities for each type of market participation. The specific expressions for these critical distances depend on the functional forms for the indirect utilities.

Lemma 2: For an equilibrium sorting to exist, the indirect utilities can cross only once. For buyers, sellers and self-sufficient households to co-exist in the market, the points of intersection should not coincide.

Proof:

This is the standard single crossing property in sorting models. The idea is that if the indirect utilities cross more than once, households will violate the transitivity of preferences assumption.

The co-existence of the three types of market participation regimes is important for the model of fuelwood extraction under a general equilibrium setting.

Expressions for critical distances, $cm*$ and $cff*$, can be derived if we assume a specific functional form for the indirect utilities. These expressions will be a function of both prices and household income and, hence, will vary by household.

Household model with transaction costs under General Equilibrium (GE)

The version of the household fuelwood production model with transaction costs is similar when the assumption of a PE is relaxed. The new feature is the additional constrain that stipulates that the total demand summed over all participating households in the market must equal all the supply of the households in the market at a given period t (i.e. the market clearing assumption). It is incorporated in the household production model as constraint (5).

$$
\begin{aligned}
&Max_{c_i,q_i,m_i} U(c_i;z)\\
&s.t.\\
&(1)\ q_i - m_i = c_i\\
&(2)\ G(q_i,x_i;z_q) = 0\\
&(3)\ \delta_i^m m_i(p_i - \delta^f t_{pc}(S)) + T - (\delta^f t_{fc}^f + \delta^m t_{fc}^m) = 0\\
&(4)\ c_i, x_i, q_i \geq 0\\
&(5)\ \sum_j^J m_{ij} = 0 \Leftrightarrow m_{ij} + \sum_{j\neq l}^J m_{il} = 0
\end{aligned}
$$

As in the previous section, the subscript *i* pertains to the commodity, AG or FU. J is the total number of households in a market. The implicit assumption is that the GE pertains only to the market for fuelwood.

The FOC from the modified household model are similar to the PE case, with the exception of the one with respect to the amount of fuelwood traded, m_{fu}, which becomes:

$$
-\mu_{fu} + \psi \left[p_{fu}(m_{fu}) + m_{fu} \frac{\partial p_{fu}\left(m_j + \sum_{l\neq j}^{J-1} m_l \right)}{\partial m_{fu}} - t_{pc}(S)\delta^f \right] = 0
$$

This FOC is identical to FOC (3) in the PE household model except for the extra term

$$m_{fu}\frac{\partial p_{fu}\left(m_j+\sum_{l\neq j}^{J-1}m_l\right)}{\partial m_{fu}}$$, which is negative for buyers and positive for sellers as fuelwood is assumed to be a normal good. This means that the GE case will increase the price for which selling households enter the market and decrease the price, which induces buyer households to exit the market, in affect making the autarky area larger in price-indirect utility space. The intuition behind this result is that households impose externalities on themselves when they participate in the market. For example, bringing an additional unit of fuelwood to sell on the market is likely to lower the price of fuelwood, making it suboptimal for the household to sell given the new lower price. The magnitude of these shifts depends on the elasticity of demand for fuelwood.

GE has a similar effect when we consider the sorting of households in dm/df space: it moves (1) *away to the forest* the critical distance *cff** that makes a household being indifferent between being autarkic and being a seller, and (2) *closer to the market* the critical distance *cm** that make a household indifferent and between being a seller and being a buyer. In other words, GE makes the autarky area bigger. The intuition for this result is based on the indirect utility being an increasing function of income and a decreasing function of the distance to the forest and the distance to the market. Please note, because of GE, the market prices change, causing discrete shifts in the indirect utility functions that lower the indirect utility. The ensuing discussion about the impact of prices on the utility function pertains to these discrete shifts that delay market entry and

not to the movement along the indirect utility curve, once the household has entered the market.

GE lowers (increases) the prices, which induce buyers (sellers) to exit (enter) the market, in effect delaying entry. Given the expression of income as a function of prices in Section I.1, under GE a lower exit market price means lower income and, hence, lower utility for buyers, *ceteris paribus* (Fig.3). Therefore, continuing to be a buyer under the new exit price will be optimal if the distance to the market decreases, *ceteris paribus*. The shorter critical distance to the market, *cm**, implies that a higher indirect utility for sellers, which implies the critical distance to the forest can increase and leave the household as well off as before.

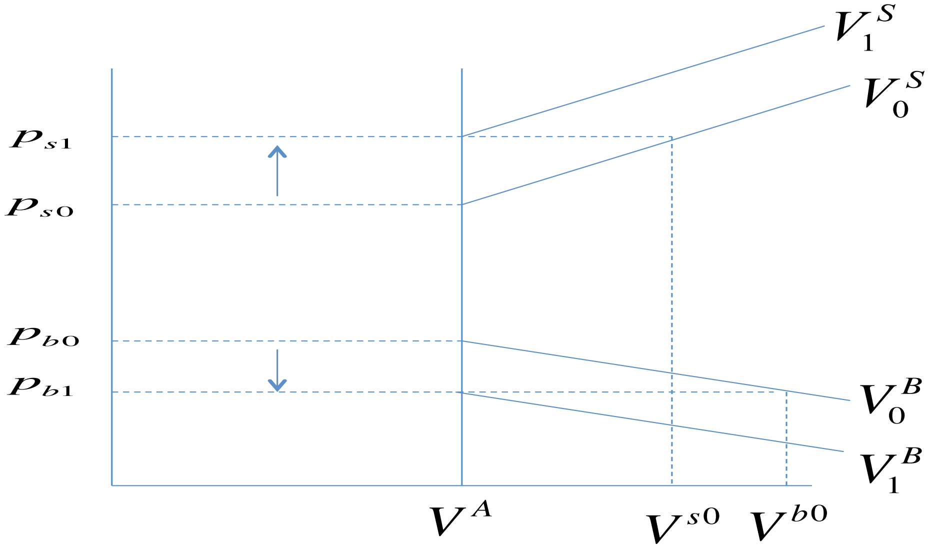

Figure 3. The impact of GE on the prices determining household participation in the market. In effect, the impact of GE is akin to increasing fixed transaction costs: decreasing the exit prices for buyers and increasing the entry prices for sellers, thus expanding the area under autarky. The shifts in the utility functions induced by the new market prices imply lower indirect utility levels, *ceteris paribus.* To see that, compare the indirect utilities for buyers at the new price p_{b1}. The initial utility function for buyers yields V^{b0} at price p_{b1}, whereas the new utility function-only V^A, which is less. Similarly, at price p_{s1} for sellers, the utility level corresponding to the initial indirect utility function is V^{S0}, which is less than

V^A. Note, the discussion above does not pertain to the relationship between prices and indirect utility for households, who have already entered the market.

Proof

The formal proof is based on the implicit function theorem. At the critical distance, cm*, let the indirect utility for a buyer household be given by:

$$V^B(p, dm) = const = c$$

$$\frac{\partial dm}{\partial p} = -\frac{\dfrac{\partial V}{\partial p}}{\dfrac{\partial V}{\partial dm}}$$

Even though by definition the indirect utility function is non-decreasing in prices for households participating in the market, GE lowers the price that induces households to exit the market and, thus, shifts downward the indirect utility for buyers, *ceteris paribus.* Thus, the numerator is negative. Because the distance to the market lowers the income and, hence, the indirect utility, the denominator is also negative. In other words, the left hand side expression is negative, suggesting that the distance to markets for buyers decreases when the exit prices decrease.

The shorter critical distance to the market implies that the household can increase the distance it travels to the forest and remain as well off as before. This implies that the critical distance to the forest will increase, creating a larger area under autarky.

In sum, even though the GE setting increases the area under autarky in p-V and dm-df space, it does not qualitatively change the predictions of our model.

Assumptions

The static household model is based on a few assumptions. First, although the households are (boundedly) rational utility maximizers, they do not exhibit any strategic behavior through time and space. In other words, the presented models assume that households do not compete for resources, allocating more than the optimal static effort to more distant forest patches, for fear that the other households in the village are going to exploit the resources at the more distant patch. Assuming that households are myopic also implies that they do not optimize their consumption through time; rather households make decisions about how much fuelwood to extract only based on the current period. This assumption is equivalent to an open access framework, which seems like a reasonable assumption for our study area, where property rights are not well defined.

The models assume no investment in forests (i.e. no one plants more indigenous trees). In our study area, some households plant exotic tree species consisting mostly of pine and eucalyptus that contribute to the depletion of aquifers and therefore can impact the microclimate and biodiversity in a given area. These trees, however, are harvested for timber when they reach a certain age. For this reason, they cannot be considered substitutes to forests consisting of indigenous trees. A related assumption is that fuelwood is gathered exclusively from forests. This may not be the case since some of our focus group participants indicated that they gather fuelwood from the fields they clear for agriculture. Yet, while fuelwood is consumed daily, clearing land for agriculture occurs before the start of each growing season and therefore cannot provide a constant supply of fuelwood.

The model also assumes that intrahousehold distributional issues are unimportant for determining labor allocation. Instead, they treat the household as a unitary Pareto efficient unit. This assumption implies an even distribution of labor (e.g. that all land is farmed with equal intensity). The model developed in this paper also assumes that all labor is homogeneous and is traded in a perfectly competitive labor market: in other words, men and women possess the same agricultural skills and family and hired labor are perfect substitutes.

Lastly, this paper assumes a deterministic setting for agricultural output. Focus group participants indicated that changing weather patterns pose significant difficulties for farmers in our study area. Recent studies have also criticized the traditional assumption of temporal independence of household activities (Fafchamps 1993; Saha 1994; Zwane 2007). In other words, the traditional models of household labor allocation in developing countries assume a static risk-free setting, in which there is no insurance and consumption smoothing opportunities. In contrast, a few studies have suggested that even though there are underdeveloped labor markets and no formal insurance mechanisms for agricultural households, in reality a rural household may be able to insure itself to some extent from fluctuations in weather or prices by choosing different levels of investment (Pope and Just 1991; Rosenzweig and Binswanger 1993; Zwane 2007). For example, households are likely to shift more resources to fuelwood production than the optimal levels according to the static household model for one period and use the additional income to finance consumption/investments in the subsequent periods (Zwane 2007). These studies suggest that the type of preferences with regards to risk determine household choices (Pope and Just 1991) and ignoring them may introduce a substantial bias in the econometric model (Saha 1994). Relaxing the deterministic setting of the spatial production model is the subject of future work.

The current version of the model assumes complete functioning markets for labor. If labor markets are not complete, the households' ability to respond to price increases in other markets may be hampered (Singh et al, 1986; de Janvry & Sadoulet, 2006). We also abstract from seasonality in the fuelwood extraction patterns. In this paper we focus on the dry season only, because the wet season, which is when all the agricultural work takes place, may introduce labor market failures.

Throughout this paper we assume that the household location is exogenous. Based on interviews with people in our study area, who are returning to the lands they used to occupy before the war, this seems like a reasonable assumption.

Finally, we assume households make decisions whether to participate in the market and how much to produce simultaneously. Whether households make market participation and crop production decisions sequentially or simultaneously is the focus of Bellemare & Barrett (2006). The authors contrast the traditional (bivariate) probit followed by a continuous model (e.g a tobit) of the amount crops produced with sequential market participation, modeled by an ordered tobit. Even though their data support the sequential decision-making, qualitatively there is very little difference between the two models. Therefore, in this paper, we abstract from the issue of sequential vs. simultaneous decision-making.

Empirical estimation of a household production model with transaction costs

The theoretical model suggests that the distance to the market distinguishes the sellers from the autarkic households, facing the same distance to the forest and forest quality: for some distance to the forest, a household is better off being a seller than being self-sufficient. Similarly, when the distance to the forest increases beyond the threshold value, a household is better off being a buyer than collecting fuelwood from the forest. Thus, the model provides useful insights for the spatial distribution of fuelwood collection and generates testable hypotheses.

In this section, we test empirically the predictions of the model:

(1) Distance to the forest determines production decisions (i.e. produce or not)

(2) Conditional on producing fuelwood, market participation is determined by the proximity to markets, *ceteris paribus*

The empirical literature on fuelwood extraction has modeled the intensive margin: how much fuelwood to collect, given certain household characteristics and proximity to forests (see the review by Albers & Robinson, 2012). Some studies acknowledge that households' choice whether to collect fuelwood from forests or produce an alternative fuel introduces sample selection issues (e.g. as in Pattanayak et al, 2004; Köhlin & Parks, 2001). While these studies account for the sample selection using Heckman's correction method (Heckman, 1979), they do not consider the option of households buying and fuelwood on the market or remaining self-sufficient.

The role of proximity to markets is featured in multiple studies focusing on the role of transaction costs for market participation of rural households, producing marketable crops (for a review on recent East Africa studies, see Barrett (2008)). Even though by focusing on agricultural crops, these studies do not include the proximity to forests, they model the household production both on the extensive and intensive margins. These studies tend to estimate the probability that a household is going to be a producer or a supplier and, conditional on that, the amount supplied (e.g. Goetz, 1992; Ouma et al, 2010). In order to account for the sample selection in the second stage, these studies apply a version of Heckman's procedure, which most often includes calculating a (bivariate) probit of market participation, generating the inverse Mills ratio, which is then used as a covariate in the model of continuous crop production. All of these studies rely on cross-sectional household survey data.

Even though theoretical work has emphasized the importance of the choice of location (i.e. forest patch) where households collect fuelwood (e.g. Robinson et al, 2008), only one study outside the fisheries literature has modeled the site choice for fuelwood collection. In MacDonald et al (2001), household fuelwood collection behavior is modeled in a Random Utility Model (RUM) framework, which includes proximity to forests and detailed set of characteristics for three sites in addition to household characteristics. In contrast to the other studies on household fuelwood collection, their paper employs repeated household choices over time.

In this paper we adopt the approaches from the market participation literature: estimating a probit model of the decision to produce fuelwood, generating the inverse Mills ratio, which we use in a regression model of the amount of fuelwood produced, which also depends on whether or a not a household decides to sell the collected fuelwood on the market. One difference with previous studies is that while we have data on the quantity of fuelwood produced, we do not have data on the demand for fuelwood.

Study area and data

Our study area spans Gulu and Oyam districts, northern Uganda. It located close to the Albertine Rift (a biodiversity hotspot), Murchison Falls National Park, Kidepo Valley National Park and Southern Sudan. Although northern Uganda does not host as many species as its neighboring regions, the vegetation in this area is very different from the ecosystems in the other parts of the country (WCS 2005). For this reason, the area contains species that are not found anywhere else in Uganda. Many of the isolated mountains in northern Uganda also contain species endemic to the Eastern Afromontane hotspot (WSC 2005). However, because of the prolonged military conflicts in the area, there have been very few biodiversity surveys in the area and much uncertainty remains about the species diversity and richness (WCS 2005).

For the empirical tests, we use geo-referenced survey data collected in 2009 (Brown, 2011). We conducted 6 focus groups with men and women separately on health and security, biodiversity and land use, and risk behavior and perception in Gulu District in June 2009. Based on the focus groups and interviews with key informants, we designed a questionnaire that was administered to 612 households in Gulu and Oyam Districts in October and November 2009 (Fig. 4 shows a map of the respondents). The households were selected through a multistage sampling approach. Using projected population numbers for Gulu and Oyam Districts from the Uganda Bureau of Statistics

(UBOS), the sample was first stratified between Gulu and Oyam districts; the second stage employed a cluster sampling procedure to select parishes, villages and households to be surveyed. In particular, we randomly selected 9 parishes in Gulu District and 6 parishes in Oyam with probability proportional to the population sizes projected by the UBOS. Within each parish a village was selected at random; from each village 40 households were drawn at random using the household rosters maintained by the village-level local administrative official. Where the rosters were out of date, we worked with the local officials and their assistants to update the lists.

The final draft of the questionnaire was 24 pages long and took approximately one hour to complete. It included sections on the demographic characteristics of the household members (age, sex, marital status, education, skills, and malaria history); the malaria knowledge, experience, subjective risk assessment, and treatment; choice experiments regarding different malaria intervention programs; household subsistence methods; land access and perceived tenure security; and sources of income and the value of assets other than land. Eight interviewers (three Langi and five Acholi) administered the survey to the male or female head of the selected households. The interviews were conducted in either Acholi or Langi depending on the primary dialect spoken by the household with the interviewers translating from an English copy of the survey. During interviewer training, four bilingual research assistants listened to each interviewer verbally translate the questionnaire and ensured that the translations are consistent with the original. The survey data contain detailed information about the household characteristics and composition, different measures of wealth and income, labor allocation patterns, the amount of fuelwood produced in addition to some land tenure characteristics.

Of the 612 completed questionnaires, for this analysis we excluded 10 as they did not have valid GPS coordinates. Combining the GPS coordinates of the surveyed households with GIS data on the administrative boundaries, land use and infrastructure for our study area allowed us to calculate important variables pertaining to the location of the households: the proximity of the household to IDP (Internally Displaced Persons) camps, roads, towns and the trading centers where markets are located. As indicated during the field visits, many households trade fuelwood and charcoal along roads. For this reason, we use the distance to the nearest road as a proxy for the distance to a local market. The distance to IDP camps in Gulu district is a proxy for the forest quality: because of the prolonged military activities in the area, prior to the end of the war households collected fuelwood only from patches close to the camps. In other words, the forest quality is likely to increase with the distance from the IDP camps in Gulu district. For Oyam district we used an interaction term of the households' distance to towns and the distance to roads, in order to proxy for environmental degradation. Our expectation is that the forest quality improves as the distance to towns and roads increases. Using the EU GlobCover landcover data for 2009, we calculated household-specific Euclidean distances to forest patches.

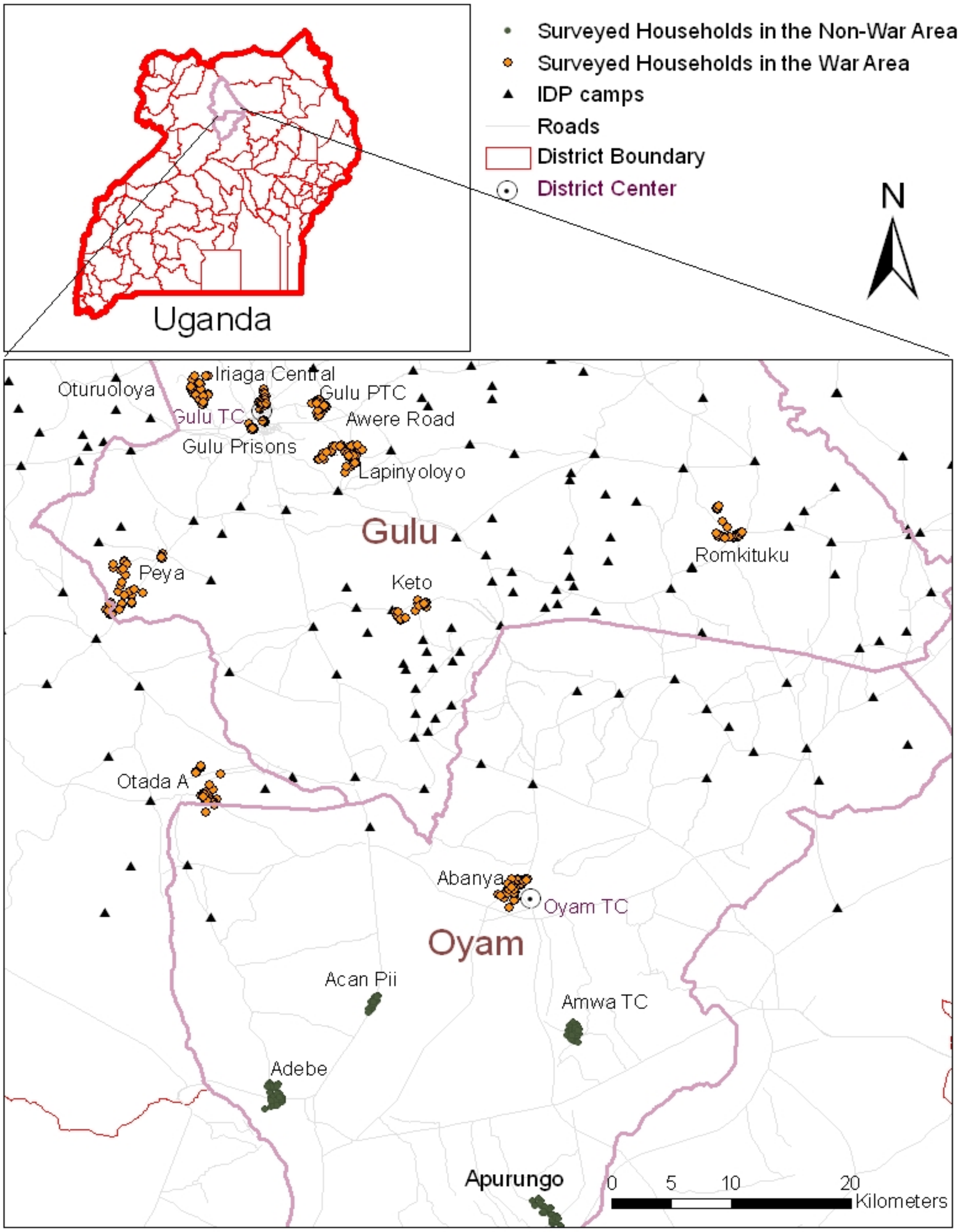

Figure 4: Map of study area. Households are considered to be in the war area if they are within 10 km from the nearest IDP camp.

Estimation

The descriptive statistics for our sample, adjusted for the multi-stage survey data collection, appear in Table 2. Our sample consists of 102 buyers, 45 sellers and 451 autarkic households. The data suggest that the buyer households are significantly different from the households producing fuelwood: the former have fewer children, but more adults living in the household; they are also more educated on average. The buyer households also tend to be wealthier based on the self-reported value of a list of 34 household items and average annual income, as well as in terms of the type of housing (with more windows, fewer thatched roofs and houses made of mud bricks). These differences are significant at the 5% level. The autarkic and seller households appear homogenous in their socio-economic and demographic characteristics.

As predicted by the static model, the buyer households are located closest to the market and farthest from the forest (Table 2). Conversely, self-sufficient households are located closest to the forest and farthest from the market, with seller households located at intermediate distances. Surprisingly, almost all of the buyer households (96/102) are located in Gulu district immediately adjacent to Gulu TC (93/96 -in the villages of Awere Road, Gulu Prisons and Iriaga Central) (Fig5, Table 2). In terms of fuelwood production during the dry season, seller household produce slightly more, but the results are not statistically significant. There seems to be a clear spatial pattern of the quantity of fuelwood produced, however: the households in close proximity to roads around Gulu TC produce significantly more than the rest of the households in our sample (Fig. 6). This pattern is consistent with our predictions about seller households.

The spatial distribution of the households in our sample also indicates that there are villages with only autarkic and seller households, but no buyers, or villages with only autarkic households (Table 2). These results weakly support the partial equilibrium assumption. Of course another potential reason for the observed patterns is that the buyer households are few, so without stratifying by distance from trading center, we may have missed them.

Table 2: Descriptive statistics for the variables used in the econometric static household model. These have been corrected for the multi-stage survey design. *designates the variables that were significantly different for the buyer group compared to the sellers and self-sufficient households.

Demographic characteristics						
Covariate	Autarkic		Sellers		Buyers	
	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.
#kids	3.21	0.07	3.49	0.09	1.86*	0.22
#adults	11.79	0.07	11.51	0.09	13.14*	0.22
Age of the HH head (in years)	44.04	1.00	39.24	0.90	36.23	1.51
%females in the HH	0.48	0.01	0.48	0.02	0.49	0.01
1 if HH head has no education	0.12	0.02	0.13	0.03	0.04*	0.01
Socio-economic characteristics						
Covariate	Autarkic		Sellers		Buyers	
	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.
Fraction HH who own a bike	0.65	0.03	0.70	0.08	0.49	0.07
Fraction HHs w/ medium-size home	0.49	0.07	0.46	0.05	0.53	0.06
Fraction HH w/ no windows	0.81	0.05	0.78	0.08	0.24*	0.13
Fraction HH w/ thatch roof	0.88	0.05	0.91	0.09	0.28*	0.18
Fraction HH w/ mud bricks	0.88	0.04	0.91	0.09	0.31*	0.15
Wealth (self-reported value of possessions, log transformed)	11.78	0.22	11.66	0.27	13.51*	0.11
Average annual income (log-transformed)	10.75	0.15	10.64	0.11	12.02	0.07
Locational characteristics & fuelwood production						
Covariate	Autarkic		Sellers		Buyers	
	Mean	Std. Err.	Mean	Std. Err.	Mean	Std. Err.
Distance to forest, in meters	2633.76	762.99	2432.44	626.84	6654.73	178.64
Distance to trading center, in meters	17387.02	2531.53	17039.63	2189.53	1722.50	652.36
Distance to roads, in meters	1078.72	278.16	879.96	106.80	178.34	77.24
Distance to shrubland, in meters	186.05	64.58	262.48	63.84	559.05	95.14
Distance to towns, in meters	5454.40	1258.77	4731.33	1445.82	6460.31	193.98
Distance to IDP, in meters	7911.86	2222.46	5012.22	1046.72	6092.22	270.95
Fraction HH in Gulu district	0.59	0.08	0.85	0.09	0.97	0.02
Bundles of fuelwood produced per typical week	4.63	0.20	4.81	0.16	NA	NA
N	451		45		102	

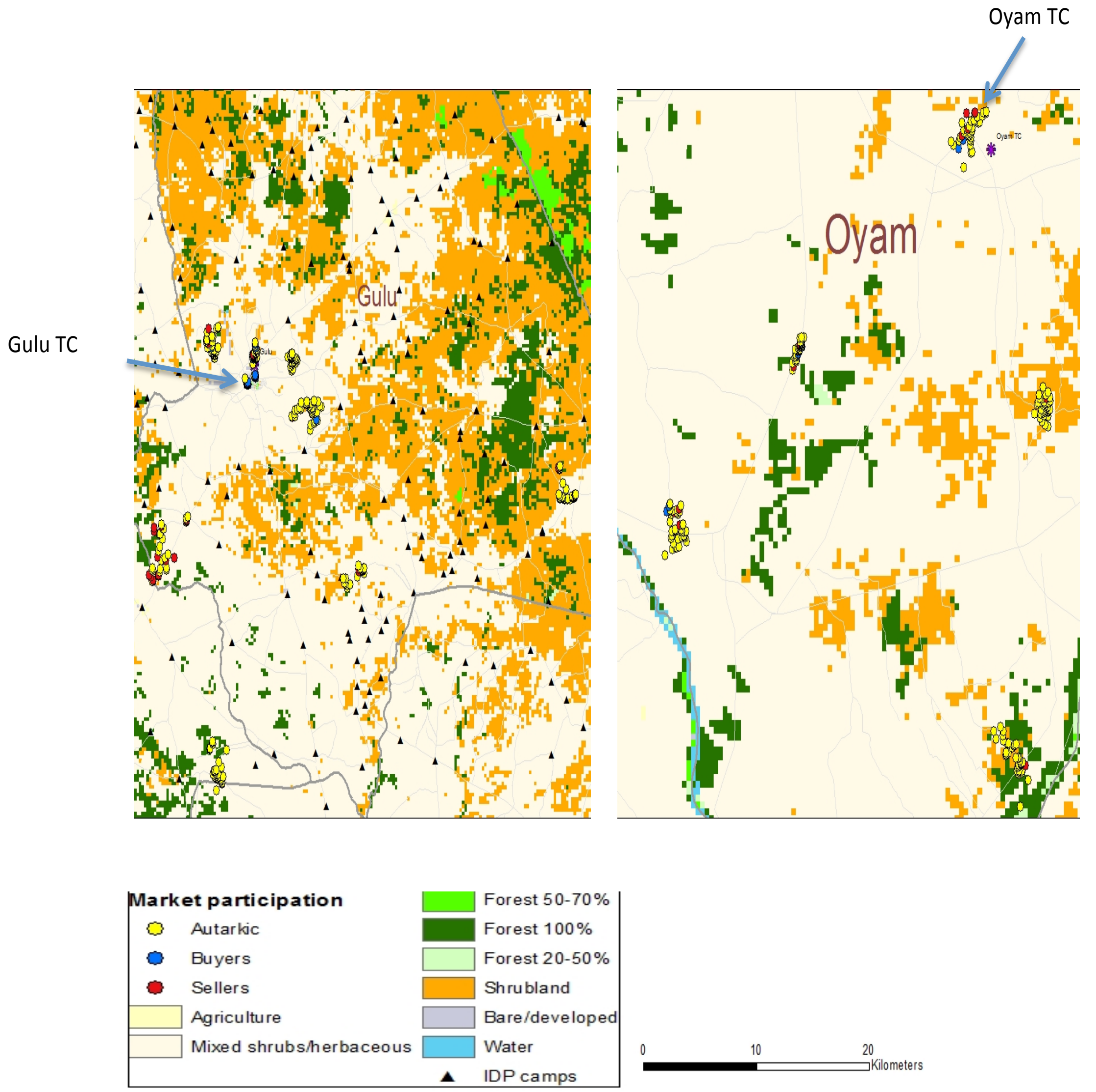

Figure 5: **This figure shows the spatial distribution of the sellers, buyers and autarkic households in our sample. The light grey lines represent roads. Note that almost all of the buyer and most of the seller households are located around Gulu TC. Our sample contains only 6 buyer and 13 seller households for Oyam district.**

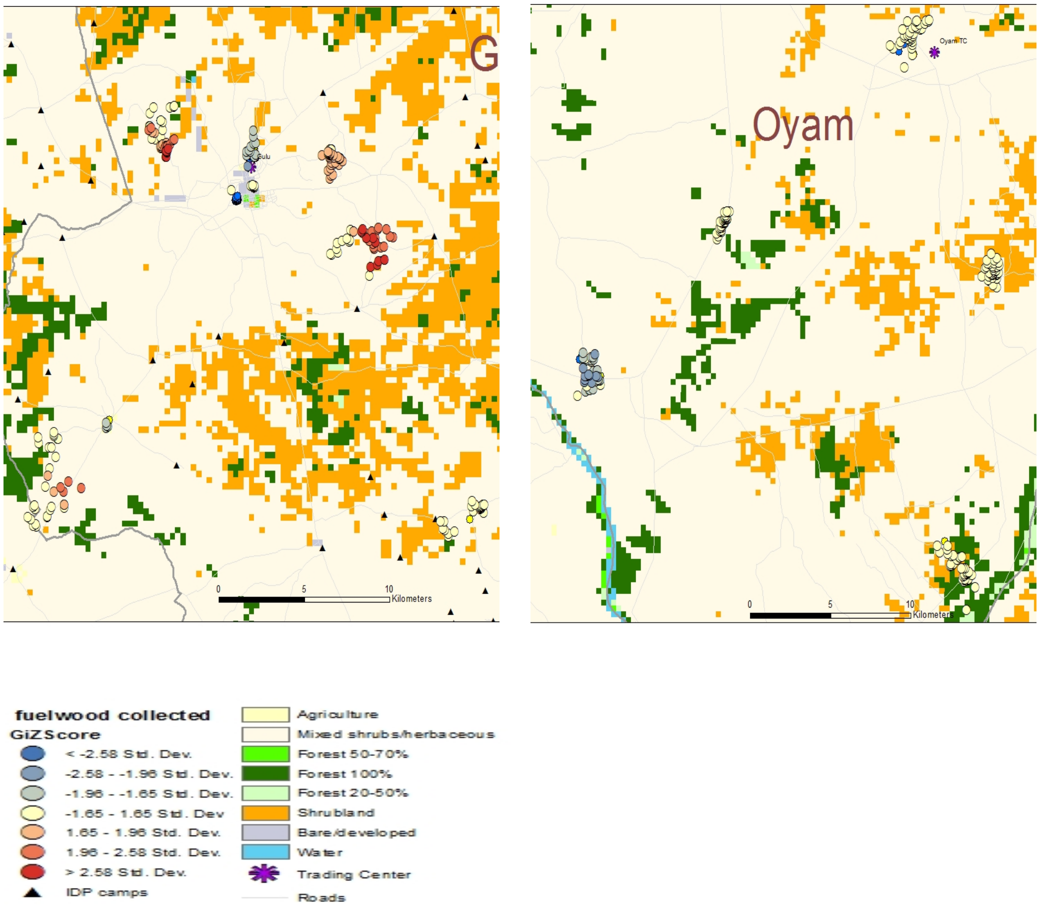

Figure 6: Spatial distribution of the amount of fuelwood collected by seller and autarkic households. Each dot represents a household in our sample. The dark red dots represent households that collect amounts that are statistically larger than the average; conversely, the blue dots represent households who collect significantly less than the average for the area. The colours represent significance levels (darkest red or blue translate into significance at the 1% level). The statistically insignificant values appear in yellow. The light grey lines are roads. Note the statistically significant clustering of very low values in Gulu town and the very high values around it. The same pattern holds true when the market is defined to encompass all households in our sample. A similar analysis for Oyam district did not indicate any statistically significant clustering of values, however. These results are based on the Getis-Ord hotspot G statistic (Getis & Ord, 1995). Please note that we didn't standardize the fuelwood collected to account for the difference household sizes. The forest cover data are of 300 m resolution and pertain to the same year the household survey data were collected.

Table 3: **Distributions of the three types of market participation regime (buyer, seller or autarkic) by village. Note, that there are some villages where only two of the types occur. Also, there appears to be a positive correlation between the fraction of buyer households in a village and the proximity to trading centers (TC). This is in support of our model and predictions.**

Gulu District						
Village	Autarkic	Buyers	Sellers	Total cluster size	Average distance to TC (m)	Average distance to forest (m)
Awere Road	11	29	2	42	1,085.41	6,626.81
Peya	24	0	15	39	18,891.83	1,722.53
Gulu PTC	35	3	2	40	4,762.36	3,307.29
Gulu Prisons	4	37	0	41	2,614.72	7,192.17
Iriaga Central	16	24	1	41	970.16	6,941.77
Keto	35	1	2	38	21,330.49	1,261.19
Lapnyoloyo	36	1	1	38	7,662.59	734.32
Oturuoloya	38	0	4	42	5,790.49	5,367.46
Romkituku	29	1	5	35	35,747.93	1,451.97
Total for district	**231**	**96**	**32**	**359**	**10,495.80**	**3,955.83**

Oyam District						
Village	Autarkic	Buyers	Sellers	Total cluster size	Average distance to TC (m)	Average distance to forest (m)
Abanya	33	2	4	39	1,844.67	3,097.63
Acampii	39	0	2	41	12,119.31	8,129.13
Amwa TC	35	1	2	37	15,924.64	542.14
Apurungo	39	0	1	40	27,355.04	1,167.72
Odebe	36	3	3	42	26,745.78	2,535.56
Otaga	41	0	1	42	28,753.24	886.03
Total for district	**220**	**6**	**13**	**239**	**18,992.00**	**2,739.35**

The ensuing empirical tests and specifications are driven by the static household model. As discussed above, the optimal market participation regime for a household depends on the fixed (the distance to the market and the distance to the forest) and proportional (forest quality) transaction costs, whereas the decision how much to produce depends only on the proportional transaction costs associated with the forest quality and the distance to the forest. In this paper we proxy the proximity to markets with the proximity to trading centers (Gulu TC and Oyam TC for our sample) , the proximity to towns and the proximity to roads, either dirt or paved. The proximity to IDP camps proxies for the degree of forest degradation in Gulu district: Because of the prolonged military conflict in the area, households were not allowed to go far from IDP camps; for this reason, given the recent time of return of the population, forest areas away from IDP camps in Gulu district are likely to be less degraded. For Oyam district we use the interaction of the household's proximity to towns and forest as a proxy for forest degradation. While we have data on the amounts of fuelwood produced by sellers and self-sufficient households, we do not have data on the amounts of fuelwood purchased by the buyer households. For this reason, we estimate the following system of equations:

(1) Probability of fuelwood production for household j as a function of the household characteristics, distance to markets, distance to forests, forest quality

    $y_3 = 1(z\delta_3 + v_3 > 0)$,

    where y_3 is a scalar and equals 1 if the household is a producer of fuelwood (i.e. either a seller or autarkic) and 0 otherwise, z is a matrix of exogenous regressors including the proximity to markets variables and the proximity to forests, δ_3 is a vector of coefficients to be estimated and v3 is the error term. We proxy the proximity to markets with the proximity to trading centers and the proximity to roads, where a significant amount of trade takes places especially in rural areas.

Given the spatial sorting model in the preceding sections, we expect that the probability of a household producing fuelwood decreases with the distance to the market and increases with the proximity to forests. For this reason, we expect that the estimated coefficients on the three distance to markets variables to have **positive** signs and the distance to forests to have a **negative** sign.

Using the predicted coefficients from the probit, we generate the inverse Mills ratio $\hat{\lambda}$.

(2) Quantity of fuelwood produced as a function of the household characteristics, proximity to forests, the inverse Mills ratio from (1) as well as whether or not a household is a seller.

$$y_1 = z_1\delta_1 + \alpha_1 y_2 + \omega\hat{\lambda} + u_1 ,$$

where y_1 is the log-transformed amount of fuelwood collected, z_1 is a subset of the exogenous covariates matrix z, y_2 is a binary endogenous variable indicating whether or not a household is a seller of fuelwood, α_1 is a scalar coefficient and δ_1 is vector of coefficients to be estimated; u_1 is the error term and $\hat{\lambda}$ is the inverse Mills ratio from (1)

(3) We instrument for the endogenous decision whether to sell fuelwood or not with the proximity to markets variables.

$$y_2 = z\delta_2 + v_2 ,$$

where y_2 is a binary variable equal to 1 if the household is a seller and 0 otherwise, z is a matrix of instruments that contains z_1 in addition to additional exogenous instruments to satisfy the identification requirements, δ_2 is a vector of estimated coefficients and v_2 is an error term. As the static spatial model of fuelwood implies, the proximity to markets affects the household decision whether to produce fuelwood or not. Yet, conditional on a household having chosen not to be a buyer, the proximity to markets does not affect the production of fuelwood. For this reason, we use the three proxies for the proximity to markets--the distance to roads, to towns and to trading centers--to instrument for the endogenous binary variable.

As predicted by the static model, we expect that the probability of a household being a seller, conditional on producing fuelwood, decreases with the distance to markets. For this reason, we expect the coefficients on the distance to market variables to be negative.

As discussed by Wooldridge (2002), the assumptions behind this procedure ((1)-(3)) are that:

(a) (z, y_3) is always observed, (y_1, y_2) is observed when $y_3=1$

(b) $(u_1, v_3) \perp z$

(c) $v_3 \sim N(0,1)$

(d) $E(u_1|v_3)=\gamma_1 v_3$

(e) $E(z' v_2)=0$

(f) $z\delta_2=z_1\delta_{21}+z_2\delta_{22}$, with $\delta_{22}\neq 0$, which is another way of writing the identification requirements for the instrumental variable.

We include all exogenous variables in the selection (1) and endogenous predictor (3) equations (Wooldridge, 2002 Ch.17). The estimation procedure summarized by (1)-(3) is valid for discrete variables, without any additional distributional assumptions (Wooldridge, 2002 Ch.17). The procedure is akin to the Heckman correction for sample selection (Heckman, 1979); the difference is in the presence of the endogenous variable.

As previous studies have pointed out, the standard errors in (2) are likely to be incorrect as $\hat{\lambda}$ is a constructed regressor (Heckman, 1979; Wooldridge, 2002). This is a concern only when the coefficient on $\hat{\lambda}$, ω, is statistically significant (Wooldridge, 2002). Regardless of the significance of ω, the coefficient estimates remain consistent (Wooldridge, 2002).

Because the data were collected using a multistage sampling design, corrections for the unequal election probability of the households need to be accounted for. In addition, we correct for within-cluster correlations, where a cluster is a village (Deaton, 1997). Not adjusting the estimates for the survey design is likely to yield biased estimates and standard errors (Deaton, 1997).

The clustered standard errors are derived using asymptotic theory based on a large number of clusters (Cameron et al, 2008). In our case, the number is relatively small (15), which creates concerns that the standard errors are downward biased, leading to rejecting the null hypothesis more often than the specified α (Cameron et al, 2008). Even though Stata uses an inflation factor of $\sqrt{\frac{G}{G-1}}$, for the standard errors to account for the small number of clusters, previous studies have suggested that it may not always be sufficient (Cameron et al, 2008). Instead, the literature has highlighted the advantages of using wild t bootstraps to generate valid standard errors, when the number of clusters is small (Cameron et al, 2007). We present the results from this technique for linear models in the Appendix F.

Results

The results from the binary models ((1) and (3)) are presented in Table 4. In the first two columns, we present the results from testing which factors affect the probability of a household being a buyer. As expected, decreasing the distance to markets increases the probability of the household being a buyer, whereas increasing the distance to forests has the reverse impact. The degree of forest degradation does not seem to be a significant factor. These results are consistent with our expectations.

In the third and fourth columns of Table 4 we present the results from the first stage of instrumental variable regression, accounting for the sample selection through the inclusion of the inverse Mills ratio. The results are also consistent with our expectations: decreasing the distances to markets increases the probability than a household will participate on the market as a seller. The forest quality was not statistically significant.

Table 5 summarizes the results from the second stage of the instrumental variable regression. The results suggest that proximity to forests and better forest quality increase the quantity of fuelwood collected as expected, but the coefficients are not statistically significant. The only statistically significant determinant appears to be the number of children in the household: this translates intuitively as more available labor.

The coefficients on the inverse Mills ratio are statistically indistinguishable from 0 in the instrumental variable model. This implies that the standard errors of the estimates are not affected by the inclusion of the generated regressor and, hence, no correction of the variance-covariance matrix is necessary (Wooldridge, 2002). However, the relatively small number of clusters from which the data were collected raises concerns that the standard errors are likely to be biased downwards, making the estimates appear more significant. Using linear probability models, we perform wild t bootstrapping and find that in the linear specifications bootstrapping increases the standard errors. However, the results were not qualitatively very different: significant predictors of the outcome variables remained such, but at a lower level of significance. The results are presented in Appendix 1.

Table 4: Results from the binary participation decisions (standard errors in parentheses). In the estimation strategy described above, the producer decision is the selection equation (the households self-select into the sample of households producing fuelwood). The decision whether or not participate on the market, conditional on producing fuelwood, is estimated in the first stage of an instrumental variable regression for the amount of fuelwood produced. We used the proximity to markets as instruments for whether or not a household is going to be a seller (or be autarkic) as the theoretical model suggests that those should not affect the quantity of fuelwood produced. The estimates have been corrected for the multi-stage survey data collection with the *svy* option in Stata 12.

	Production decision (1 if producer)		**Seller decision (1 if a seller)**	
Covariate	**Probit**	**OLS**	**Probit**	**OLS**
#kids	0.27** (0.12)	0.03* (0.02)	0.02 (0.04)	0.001 (0.009)
Age of the HH head, in years	0.02** (0.01)	0.001 (0.002)	-0.01*** (0.00)	-0.003* (0.001)
%females in the HH	0.23 (0.32)	-0.04 (0.04)	0.12 (0.31)	-0.03 (0.05)
1 if the HH has a bike	-0.10 (0.12)	0.001 (0.02)	0.12 (0.29)	0.03 (0.06)
1 if house made of mud bricks	-0.05 (0.16)	0.15** (0.05)	0.11 (0.23)	0.05 (0.05)
1 if no HH head has no education	-0.39 (0.25)	-0.04* (0.02)	0.32 (0.19)	0.06 (0.04)
Distance to trading centers, in km	0.14 (0.09)	0.01** (0.004)	-0.06 (0.23)	0.01 (0.03)
Distance to towns, in km	0.30 (0.44)	-0.01*** (0.003)	-0.20** (0.08)	-0.05*** (0.02)
Distance to roads, in km	1.15** (0.40)	0.10*** (0.03)	-0.17 (0.18)	-0.04** (0.01)
Distance to forest, in km	-0.32* (0.18)	-0.01 (0.01)	0.37** (0.17)	-0.02 (0.03)
Forest degradation (higher values-less degraded)	-0.48 (0.31)	-0.04*** (0.01)	-0.17 (0.16)	0.06*** (0.01)
1 if Acholi ethnicity		0.05 (0.05)	0.60* (0.31)	
1 if house has no windows			-0.05 (0.17)	-0.03 (0.05)
Inverse Mills ratio			-0.82 (0.93)	-0.12 (0.08)
1 if Gulu district				0.14** (0.06)
Constant	0.71 (1.41)	0.58*** (0.17)	-1.10 (0.68)	0.14 (0.14)
N	571	582	459	465

Significance levels: ***1%, **5%, *10%

Table 5: **Results for the estimation of the amount of fuelwood produced as a function of the household location with respect to the forest, the forest quality and household characteristics (standard errors in parentheses). The statistical insignificance of the constructed inverse Mills ratio suggests that the standard errors of the covariates are likely unaffected by the introduction of the constructed regressor (Wooldridge, 2002). However, the relatively small number of clusters raises concerns of Type I error.**

Quantity fuelwood produced during a typical week (log transform)	**Estimates**
#kids in a HH	0.05*** (0.01)
Age of the HH head in years	-0.01 (0.003)
%females	-0.26 (0.35)
1 if the HH has a bike	0.08 (0.06)
1 if Gulu district	0.23 (0.46)
1 if house with thatch roof	-0.02 (0.13)
1 if HH head has no education	0.01 (0.18)
Distance to forest, in km log transform	-0.06 (0.06)
Forest degradation (higher values=less degradation)	0.06 (0.04)
Autarkic HH (endogenous)	-0.43 (0.57)
Inverse Mills ratio	-0.67 (0.40)
Constant	1.48 (0.30)
N	459

Significance levels: ***1%, **5%, *10%

Conclusions

This study adds to the literature on fuelwood collection by modeling space as comprised of discrete forest patches located at varying distances from the households and markets. The static household production model with transaction costs adapted from Key et al (2000) generates spatial predictions of households sorting in space by market participation regime depending on their proximity to forests and markets. We show that allowing for general equilibrium makes the autarky area larger compared to a partial equilibrium setting, but does not impact the nature of the household sorting in space. Our predictions of households sorting in space, with buyers closest to the market and autarkic households closest to the forest are supported by empirical evidence from northern Uganda. One limitation of the current study is that the survey design did not aim to sample the spatial distributions of households in terms of their market participation regimes. Yet, we are still able to capture spatial patterns of fuelwood production.

The importance of the model is that it allows us to make forecasts of potential spillover effects from the introduction of a conservation policy like protected areas (e.g., Smith & Wilen, 2003), which make certain patches unavailable to households. Using data on a household location with respect to the forest and markets, we can make predictions about the optimal market participation regime and the forest patch if the household decides to collect fuelwood. Thus, understanding household spatial behavior can help mitigate the spillover effects on unprotected forest patches. Such models have important implications for evaluating the performance of conservation policies as well: currently, studies aiming to quantify the impact of protected areas *assume* spillover effects occur in locations immediately adjacent to protected areas; they test for the presence of spillover effects by using arbitrary distances, for which no theoretical justification exists (Miteva et al, 2012).

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