Fuelwood Source Substitution and Shadow Prices in Western Kenya

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Abstract: Deforestation in Sub-Saharan Africa remains a substantial problem. Increasing scarcity of fuelwood can be significant burden to households, as fuelwood is a key component of the energy profile of a rural Sub-Saharan household. However, households do not only collect their fuelwood from off-farm, but also produce it on-farm and purchase it from the market. This paper studies substitution between fuelwood sources for rural Kenyan households. Conducting analysis using shadow prices for household fuelwood in a non-separable theoretical framework, we find that strict gender divisions in household labor contribute to a lack of substitution between fuelwood sources. Because fuelwood production on the farm is more sustainable than off-farm collection, gender divisions inhibit reforestation efforts in this area. This paper finds a direct linkage between women and environmental well-being, and concludes that reforestation efforts in SSA will likely be ineffective until labor substitution between genders increases.

1 Introduction

Much of the world's population, especially the poor in rural areas of developing countries, rely on biomass (crop residues, animal dung, and fuelwood) for basic household energy requirements. In rural Sub-Saharan Africa (SSA), for example, 80 percent of the population depends on biomass for daily cooking fuels with most of the biomass coming from fuelwood (IEA, 2014). This dependency on fuelwood carries obvious environmental and health implications.

Greenhouse gas (GHG) emissions from residential energy use in SSA are considerable: in 2000 the net GHG emissions totaled 79 million metric tons of carbon (MtC) with 61 percent due to fuelwood use (Bailis et al. 2005). They are also projected to increase. Under business as usual scenario, the cumulative GHG emissions will reach 6.7 billion tons of carbon by 2050, or 134 MtC per year – the equivalent of more than four large coal fired power plants operating at full capacity over the period (WWF, 2007). Increasing scarcity of fuelwood also contributes to deforestation. Deforestation accounts for 6-17 percent of global GHG emissions (Baccini et al. 2012), and other environmental concerns include the loss of animal habitat and decreases in nutrients and moisture in soil leading to desertification (WMO, 2005). The last decade witnessed 13 million hectares of trees lost every year globally (FAO, 2010) and 290 thousand hectares lost specifically in Africa (Joint Research Center, 2013). Findings also show that the major contributor to deforestation in SSA is fuelwood collection and charcoal production (Hosonuma et al. 2012). Another concern is the impact of biomass fuels on health. The smoke is associated with millions of deaths per year due to respiratory diseases (Lin et al., 2007).

In addition, the use of fuelwood as an energy source places a particular burden on women in the household, given that women in SSA are primarily responsible for both fuelwood collection and food preparation so that the health effects of smoke from biomass fuels is largely borne by women. Moreover, increasing scarcity of fuelwood means increasing collection times. This adds to the labor burden of women, as traditional roles such as raising children, cooking, and other household tasks create a "double workday" and mean that women often work much longer hours than their male spouses (Blackden and Wodon, 2006; Kes and Swaminathan, 2006).

Sustainable forestry management has been viewed as a potential remedy for these related problems. On-farm fuelwood production and agroforestry, for example, can both reduce environmental impacts of solid biomass use and mitigate household search costs associated with deforestation. Since the 1970s, many research and non-governmental organizations have focused on promoting agroforestry in SSA,[1] with many projects paying particular attention to transferring agroforestry skills to women (Maathai, 2003; Bradley and Huby, 1993). Teaching women agroforestry skills has been argued to help shift on-farm tree management from non-fuelwood to fuelwood usage and increase the absolute number of farm trees.

Most of the empirical literature examining household energy needs thus far has focused on understanding the substitution between aggregated fuelwood consumption (or consumption from a single source such as fuelwood collected) and other biomass options such as agricultural residues, and relied on the data from South Asia, with only a few studies of fuelwood demand in SSA (some of the studies are summarized in Table 1).

The existing literature has argued that as fuelwood scarcity increases, households may react to the increasing implicit cost of obtaining this resource in various ways: substituting other fuels, adopting higher efficiency stoves, and increasing per unit collection times. The

[1] In Kenya, for example, the Green Belt Movement and Stockholm Environmental Institute are two of the well-known organizations.

empirical evidence in support of these hypotheses, however, has been mixed. Several studies that look at the substitution of fuelwood with crop residues and animal dung find no evidence of substitution (Pattanayak et al., 2004; Palmer and MacGregor, 2009), while others find evidence of complementarity between fuelwood and cut grass and leaf fodder (Cooke, 1998a), and animal dung (Mekonnen, 1999). In addition to or instead of purchasing fuelwood, a household can adopt technology to increase the efficiency of fuelwood such as improved stoves. Amacher et al. (1993; 1996; 1999) and Pattanayak et al. (2004), for example, find that owning more efficient stoves leads to a significant decrease in fuelwood consumption, while Heltberg et al. (2000) find no effect. The response of labor supply to increases in scarcity of fuelwood (and in implicit cost of fuelwood) is always positive, but mixed as to whether the magnitude is greater than or less than the magnitude of the own-price elasticity (Amacher et al., 1996; Cooke, 1998a; Heltberg et al., 2000; Palmer and MacGregor, 2009).

Insert Table 1

To our knowledge, no existing study has specifically focused on the substitution between three different sources of fuelwood in response to increasing fuelwood scarcity. In most of the developing world, households collect fuelwood from off-farm, produce fuelwood on-farm, and purchase fuelwood from the market or other households. In perfectly functioning fuelwood and labor markets, the costs of the fuelwood sources would be equal. Market imperfections, however, can create divergences between the household-specific implicit or shadow prices of the separate sources and the market price, and lead to source-specific own-price and cross-price elasticities. Several studies that estimate demand for off-farm collection and on-farm fuelwood production do not estimate cross-price elasticities to analyze substitution (Amacher et al., 1993; Heltberg et al., 2000). They use collection time as a proxy variable for the shadow price, and in the case of Heltberg et al. (2000) combine fuelwood produced on-farm with crop residues and animal dung. In contrast, we analyze both own-price elasticities for three separate fuelwood sources using shadow prices and market prices as well as substitution patterns between the sources as illustrated by cross-price elasticities. An understanding of household substitution between fuelwood sources has significant policy importance as it reveals whether households treat fuelwood as a homogeneous product, as is often implicitly assumed in the literature, or whether it is a differentiated product based on its source. If it is indeed differentiated by households and strong preferences exist for certain fuelwood sources, this could have ramifications for the effectiveness of policies promoting agroforestry or other sustainable fuelwood sources.

The main goals of this paper are thus to investigate 1) whether household fuelwood sources are close substitutes or differentiated products and 2) whether gender roles persist in fuelwood production and collection. Assuming fuelwood markets are imperfect and household production and consumptions decisions are non-separable, we extend the agricultural household model to focus on the substitution between different fuelwood sources and on the role of household's labor endowment (following Heltberg et al., 2000 and Palmer and MacGregor, 2009). We estimate household shadow prices using household-specific wages for men and women. Since not all households engage in off-farm labor markets, we first impute male and female wages using maximum likelihood estimates of the Heckman estimator to control for selection bias. We then estimate demand equations for different fuelwood sources, including respective shadow prices, fuelwood market price, and wages as independent variables. To control for potential selection into three fuelwood groups (households that produce fuelwood on-farm, collect it off-farm, and purchase), we also estimate demand equations controlling for selection bias. And we use instruments in the spirit of Hausman et al. (1994) (borrowed from the demand literature) to control for possible endogeneity in the shadow price and market price variables.

The data used in the estimation come from a detailed production and consumption survey of over 300 households in the western Kenya highlands (in the Rift Valley, Nyanza, and Western provinces). Kenya makes a good case study to address our research questions due to the high consumption rates of fuelwood both produced on-farm and collected off-farm, and the changing gender roles. Moreover, given that the majority of existing studies focus on South Asia, our analysis adds needed evidence of fuelwood consumptions patterns in East Africa.

We show that cross-price elasticities between fuelwood sources are very low, suggesting that Kenyan households do not substitute easily between fuelwood sources. As expected, we also find that own-price elasticities are negative and inelastic. As an implicit cost increases for a particular source of fuelwood, households decrease their consumption of that fuelwood source with only limited substitution with other fuelwood sources. The limited substitution between fuelwood sources is also partially explained by gender roles. The data and our analysis confirm that women are primary collectors of fuelwood off-farm, while men are primary producers of fuelwood on-farm. It is the lack of labor substitutability between fuelwood tasks that leads to limited opportunity to substitute between fuelwood sources.

The rest of the paper is organized as follows. In section 2 we describe the background to the research area and data collected in western Kenya in 2011-2012, and in section 3 we present a non-separable agricultural household model that takes into account the various fuelwood sources and household labor endowment. In section 4 we describe our empirical strategy, which includes maximum likelihood estimations of the Heckman estimators to control for selection bias in the imputed wages and fuelwood source groups, and two-stage least squares to control for endogeneity in the shadow prices. We present our results in section 5 and highlight policy implications in section 6.

2 Background

Forests cover less than seven percent of Kenya's land area, yet they make a significant contribution to the national economy and provide crucial direct and indirect goods and services to its people (Rep. of Kenya, 2014). Historically, Kenyan forests have been cleared both to create land for agriculture and for sale and subsistence use of forest products. In recent years, deforestation has been largely driven by the latter, as private consumption of forest products doubled between 2000 and 2010 (Crafford, et al., 2012). Deforestation rate has averaged about 5,000 hectares per year in the Kenyan montane forests (Crafford, et al., 2012) and has had substantial effects on many aspects of the Kenyan environment and economy. Deforestation, for example, has increased ambient surface temperatures and increased incidences of malaria (Zhou et al. 2007; Yasuoka and Levins 2007), increased sedimentation due to erosion in water harming fish habitats (Simonit and Perrings, 2011), and reduced water flow for irrigation and energy production through hydropower plants (Crafford, et al., 2012). The impacts of deforestation have been estimated to cost the Kenyan economy 5.8 billion Kenyan shillings (69 million US dollars) in 2010 (Crafford, et al., 2012). Thus, despite the relatively small amount of forested land in Kenya, the impact of deforestation continues to be substantial both to the nation's economy as a whole and to individual households.

Roughly 80 percent of Kenyan households and businesses still depend on fuelwood as a primary energy source (Rep. of Kenya, 2014). The Kenyan government and non-governmental organizations have promoted private tree cultivation on household lots in an effort to prevent further deforestation (see, for example, Kenya Forest Service (2009); Mathu (2011)), so that fuelwood in rural Kenya is often both collected from off-farm sources as well as produced on private woodlots on the farm. In many villages, fuelwood is also purchased either from neighbors or local markets.

The labor division in fuelwood sourcing is also strict. Similarly to other countries in SSA, women are engaged both in "productive" activities, such as fuelwood and water collection, and "reproductive" activities, such as cooking, cleaning, and childcare (Blackden and Wodon, 2006). Men, on the other hand, are generally engaged only in "productive" activities such as crop, tree and livestock production and off-farm work. The "double workday" for women often means that women work longer hours than men, which limits their opportunity for exposure to the off-farm labor market (Blackden and Wodon, 2006; Kes and Swaminathan, 2006).

Specifically in Kenya, qualitative studies from the early 1990s have shown strong cultural taboos against women participating in on-farm tree management (Chavangi and Adoyo, 1993). In the Kakamega region of western Kenya, for example, the belief exists that "if a woman plants a tree, she will become barren" (Chavangi and Adoyo, 1993, pg. 66). This labor division has also been demonstrated in other developing countries. In Nepal and India, women and children are the primarily collectors of fuelwood and men are the primary producers (Amacher et al., 1993; Heltberg et al., 2000). In our theoretical model, we assume that this gender disparity continues to exist in rural western Kenya, but seek to empirically test this assumption in our estimation.

The household data used in our analysis were collected in 2011-2012 in the basins of the Nyando and Yala rivers, which feed into Lake Victoria. Over 300 households in 15 villages of the Rift Valley, Nyanza, and Western provinces were interviewed on a wide range of standard Living Standards Measurement Survey topics.[2] The survey included a detailed module on household energy consumption and production from all available sources.

Insert Table 2

The vast majority of households in the sample use fuelwood as a primary cooking energy source. Many households also acquire their fuelwood from more than one source, such as collecting fuelwood off-farm and producing fuelwood on-farm. Following the methodology of Acharya and Barbier (2002) and Palmer and MacGregor (2009), if a household is in multiple fuelwood groups, we consider it in each of the groups in which it participates. For example, a household that collects and produces fuelwood is considered to be in the collecting fuelwood group and producing fuelwood group. As a consequence, the total number of observations of all the fuelwood groups added together is greater than the total households in the sample.

Table 2 includes summary statistics of the full sample of households and also subdivided into three source groups. The average annual household income is 127,827 Kenyan Shillings

[2] The data collection, including the sampling procedure and methods, is described in great detail in Berazneva (2015). For this analysis, we omit two households that do not use any fuelwood, and several other households with missing income or wealth variables. Due to outliers in the reported male wages, we also omit households in the top one percent of average male wages.

($1,500), and the median income is 79,540 ($950). Roughly ten percent of household income is from remittances and on average more than half of income is earned off-farm.

Several differences between source groups are immediately apparent. Fuelwood buyers, for example, have larger households, higher annual incomes, higher wages for men and women, more education, and less land area than the other two groups. All of these differences are to be expected. Households with higher incomes can more readily afford to buy fuelwood; larger household sizes translate to more time spent collecting or producing fuelwood; and smaller land areas mean less room to produce sufficient fuelwood on-farm. Collectors, on the other hand, have the lowest income of the three groups, have younger household heads, fewer number of on-farm trees, smaller land sizes, less wealth, and are closer to the village center. Lower incomes prevent fuelwood purchasing, fewer on-farm trees imply smaller fuelwood production, and being closer to the village center implies a lower opportunity cost of collecting as collection often takes place on neighboring land parcels.

Finally producers have larger land holdings, a greater absolute number of trees, larger herd size, lower wages for men and women, and a smaller share of income earned off the farm. Larger household land holdings suggest lower opportunity costs for fuelwood production all else equal, as more land is available for tree cultivation. A larger herd size and smaller share of income earned off-farm suggest that producers spend more of their labor working on-farm. This may lead to lower opportunity costs of production as farmers may be able to practice tree management in-between other on-farm activities.

3 Theoretical Household Model

In rural Kenya, as elsewhere in SSA, most of a typical household's consumption is self-produced. Given likely imperfections in markets for both labor and goods, market wages may not be directly applicable for analysis of household opportunity costs when it comes to fuelwood collection and production (Skoufias, 1994; Amacher et al., 1996). While hired labor is used in this area for agricultural activities, no households in the sample hired labor for fuelwood acquisition. In a constrained labor market, labor allocated to private energy collection and production is thus subject to an unobserved shadow wage that forms the basis of a household's production decisions. In this context, household production and consumption decisions are decided simultaneously and can be characterized as non-separable (Singh et al., 1986).

In addition, in our dataset 63 percent of households consuming fuelwood purchased none from the market. The opportunity cost (also known as shadow price or shadow cost) of fuelwood for these households can therefore be substantially different from the market price. Strauss (1986), Jacoby (1993) and Skoufias (1994) were among the first to develop the concept of shadow wages and shadow prices in a general agricultural context, and Amacher et al. (1996) were first to apply it specifically to fuelwood. Heltberg et al. (2000) and Palmer and MacGregor (2009) expanded the non-separable agricultural household model to focus on traditional energy substitutes. We build on their model and include three different fuelwood sources (collected off-farm, produced on-farm, and purchased), as well as the substitution of traditional fuels (e.g., crop residues) and other alternatives (e.g., kerosene) with fuelwood.

More formally, let a representative agricultural household maximize a monotonic, continuous, quasi-concave utility function U:

$$\underset{C_E, C_X, C_L^M, C_L^F}{MaxU} = U(C_E, C_X, C_L^M, C_L^F; z^h) \tag{1}$$

where C_E stands for consumed goods requiring energy inputs, C_X is all other consumed goods, C_L^M is leisure consumed by men in the household, C_L^F is leisure consumed by women in the household, and z^h are household characteristics that affect consumption. Household goods C_E are produced according to function Θ using a mixture of energy types and technology:

$$C_E = \theta(C_{FW}, C_B, C_A; S) \tag{2}$$

Here, C_{FW} represents fuelwood consumed, which can be from fuelwood collected, self produced, or purchased. C_B stands for other traditional biomass fuels such as crop or animal residues usually produced on farm, C_A represents consumption of more relatively advanced fuels such as kerosene, and S represents stove technology.

We assume that women are the primary collectors of fuelwood and men mostly produce fuelwood on the farm, as has been reported in the literature both for South Asia (Amacher et al., 1993; Heltberg et al., 2000) and for western Kenya (Chavangi and Adoyo, 1993). We also assume that male and female labor is not perfectly substitutable. Therefore the consumption of leisure in the model is divided between women and men, $C_L^{F,M}$, and is given by:

$$C_L^{F,M} = L^{F,M} - l_{AG}^{F,M} - l_{off}^{F,M} - l_{FW}^{F,M} \tag{3}$$

where L is the total endowment of labor, l_{AG} is labor devoted to agricultural activities, l_{off} is off-farm labor, and l_{FW} is labor allocated to fuelwood collection or production.

Production for fuelwood collected off-farm and fuelwood produced on-farm is given as the following continuous, quasi-concave functions of household labor:

$$q_{FW}^P = f_{FW}^P(l_{FW}^M, a_{FW}^P; z_{FW}^P) \tag{4}$$

$$q_{FW}^C = f_{FW}^C(l_{FW}^F, a_{FW}^C; z_{FW}^C) \tag{5}$$

where q_{FW} is the quantity of fuelwood produced or collected, a_{FW} are household-specific factors influencing fuelwood collection or production, and Z_{FW} are other household characteristics. As noted above, female labor is used by the household for fuelwood collection and male labor for fuelwood production.

For simplicity[3] we assume that all fuelwood collected, produced, or purchased by the household is consumed such that

$$C_{FW} - q_{FW}^P - q_{FW}^C \geq 0 \tag{6}$$

The amount is positive for buyers and equal to zero for non-buyers. The agricultural production, q_{AG}, is a function of male and female labor, lAG, other agricultural inputs such as land, a_{AG}, agricultural residues used for soil fertility management and feed, q_B, and other household endowments, Z_{AG}, given by:

[3]Only twelve households in the sample (3.8 percent) sell fuelwood.

$$q_{AG} = f_{AG}(l_{AG}^M, l_{AG}^F, a_{AG}; z^{AG}) \tag{7}$$

$$q_B = \alpha q_{AG} - a_{AG} \tag{8}$$

Where α is the proportion of the agricultural production that results in crop residues. q_B is therefore the amount of crop residues that are left after use for agricultural production.

The household budget constraint for a household is given by Equation 9:

$$P_X C_X + P_{FW}(C_{FW} - q_{FW}^P - q_{FW}^C) + P_A C_A = P_{AG} q_{AG} + w_M l_{off}^M + w_F l_{off}^F + V \tag{9}$$

where P_X, P_{FW}, P_A, P_{AG}, are prices of respective goods, $w_.$ are wage rates, and V represents other household income such as remittances.

Non-negativity constraints for this model are:

$$q_i \geq 0 \qquad i = FW^P, FW^C, AG, B$$

$$c_j \geq 0 \qquad j = E, X, l^M, l^F, FW, B, A$$

$$l_k \geq 0 \qquad k = AG^M, AG^F, off^M, off^F, FW^F, FW^M$$

Thus, assuming an internal solution, we have the following Lagrangian:

$$\begin{aligned}\mathcal{L} = & U[\theta(C_{FW}, C_B, C_A; S), L^M - l_{AG}^M - l_{off}^M - l_{FW}^M, L^F - l_{AG}^F - l_{off}^F - l_{FW}^F; z^h] \\ & - \lambda[P_X C_x + P_{FW}(C_{FW} - q_{FW}^P - q_{FW}^c) + P_A C_A - P_{AG} q_{AG} - w_M l_{off}^M - w_F l_{off}^F - V] \\ & - \mu_{AG}[q_{AG} - f_{AG}(l_{AG}^M, l_{AG}^F, \alpha q_{AG} - q_B; z_{AG})] - \mu_{FW}^P[q_{FW}^P - f_{FW}^P(l_{FW}^M, a_{FW}^P; z_{FW}^P)] \\ & - \mu_{FW}^C[q_{FW}^C - f_{FW}^C(l_{FW}^F, a_{FW}^C; z_{FW}^C)] - \eta[C_{FW} - q_{FW}^P - q_{FW}^C)]\end{aligned} \tag{10}$$

Selected first order conditions for utility maximization are given as:

$$\frac{\partial \mathcal{L}}{\partial C_{FW}} = \frac{\partial U}{\partial \theta} \frac{\partial \theta}{\partial C_{FW}} - \lambda P_F - \eta = 0 \tag{11}$$

$$\frac{\partial \mathcal{L}}{\partial C_X} = \frac{\partial U}{\partial C_X} - \lambda P_X = 0 \tag{12}$$

$$\frac{\partial \mathcal{L}}{\partial q_{AG}} = \lambda P_{AG} + \mu_{AG}\left[\alpha \frac{\partial f_{AG}}{\partial a_{AG}} - 1\right] = 0 \tag{13}$$

$$\frac{\partial \mathcal{L}}{\partial q_{FW}^{P}} = \lambda P_{FW} - \mu_{FW}^{P} + \eta = 0 \tag{14}$$

$$\frac{\partial \mathcal{L}}{\partial q_{FW}^{C}} = \lambda P_{FW} - \mu_{FW}^{C} + \eta = 0 \tag{15}$$

$$\frac{\partial \mathcal{L}}{\partial l_{AG}^{F,M}} = \mu_{AG} \frac{\partial f_{AG}}{\partial l_{AG}^{F,M}} - \frac{\partial U}{\partial C_{L}^{F,M}} = 0 \tag{16}$$

$$\frac{\partial \mathcal{L}}{\partial l_{off}^{F,M}} = \lambda w^{F,M} - \frac{\partial U}{\partial {C_L}^{F,M}} = 0 \tag{17}$$

$$\frac{\partial \mathcal{L}}{\partial l_{FW}^{F}} = \mu_{FW}^{C} \frac{\partial f_{FW}^{C}}{\partial l_{FW}^{F}} - \frac{\partial U}{\partial C_{L}^{F}} = 0 \tag{18}$$

$$\frac{\partial \mathcal{L}}{\partial l_{FW}^{M}} = \mu_{FW}^{P} \frac{\partial f_{FW}^{P}}{\partial l_{FW}^{M}} - \frac{\partial U}{\partial {C_L}^{M}} = 0 \tag{19}$$

$$C_{FW} - q_{FW}^{P} - q_{FW}^{C} \geq 0 \tag{20}$$

Rearranging the first order conditions produces a number of important considerations. Using equations 11, 14, and 15, we see that the marginal utility of fuelwood consumption is equal to the shadow price of fuelwood:

$$\frac{\partial U}{\partial \theta} \frac{\partial \theta}{\partial C_{FW}} = \lambda \left(P_F - \frac{\eta}{\lambda} \right) = \mu_{FW}^{P} = \mu_{FW}^{C} \tag{21}$$

where μ_{FW}^{P} and μ_{FW}^{C} are, respectively, the shadow prices of producing and collecting fuelwood, which in equilibrium with an internal solution are equal. In practice, however, these shadow prices can differ due to household preferences, insubstitutability of labor between male and female household members, and environmental factors, among other reasons.

First order conditions with respect to female and male labor also produce interesting results (using equations 16 through 19 above):

$$\frac{\partial U}{\partial {C_L}^{F}} = \mu_{FW}^{C} \frac{\partial f_{FW}^{C}}{\partial l_{FW}^{F}} = \mu_{AG}^{F} \frac{\partial f_{AG}}{\partial l_{AG}^{F}} = \lambda w^{F} \tag{22}$$

$$\frac{\partial U}{\partial {C_L}^{M}} = \mu_{FW}^{P} \frac{\partial f_{FW}^{P}}{\partial l_{FW}^{M}} = \mu_{AG}^{M} \frac{\partial f_{AG}}{\partial l_{AG}^{M}} = \lambda w^{M} \tag{23}$$

Equations 22 and 23 demonstrate that the marginal utility of leisure is equal to the marginal value product of fuelwood production/collection and the marginal value product of agriculture, which also depends on the wage rate for men and women.

Non-separability of households' production and consumption decisions, thus, imply that household labor activities are subject largely to household-specific unobserved opportunity costs or shadow prices. In particular, household consumption of fuelwood depends on the household-specific shadow price (for non-buyers), which in this model is divided into the shadow prices of production, μ^P_{FW}, and collection, μ^C_{FW}.

First order conditions can be further re-written to imply the following reduced-form equations for the quantity of fuelwood produced on-farm, q^P_{FW}, and collected off-farm, q^C_{FW}:

$$\left.\begin{array}{l} q^P_{FW} \\ q^C_{FW} \\ q^B_{FW} \end{array}\right\} = f(P_{FW}, P_X, P_{AG}, P_A, w^{F,M}, z^h, z^{P,C}_{FW}, L, S, V) \tag{24}$$

where q^P_{FW}, q^C_{FW}, and q^B_{FW} are the quantities of fuelwood produced, collected, and bought respectively. Given the first order conditions it is clear that the price of fuelwood, P_{FW} is not the market price for the case of fuelwood collected or produced in a labor constrained market, but is endogenous and a function of shadow costs. The wage rate, $w^{F,M}$, is also not exogenous but a function of implicit household wage rates.

4 Estimation Strategy

In order to estimate the demand equations specified by Equation 24, we first need to construct shadow prices that take into account the opportunity costs associated with the respective tasks. The shadow price of collecting, for example, implies that, ceteris paribus, "the longer it takes to collect a unit of fuel and/or the higher the opportunity cost of labor used, the higher the cost of collecting a unit of fuel" (Mekonnen 1999). The variable used to represent the shadow prices for households is varied in the literature. Cooke (1998a and 1998b), Mekonnen (1999), and Baland et al. (2010), for example, use the opportunity cost of labor (shadow wage) multiplied by the time spent collecting each unit of fuelwood. The data on amounts of fuelwood collected, however, are often difficult to obtain so that Amacher et al. (1993), Heltberg et. al. (2000) and Palmer and MacGregor (2009) use the time spent collecting fuelwood as a proxy. This variable, however, does not capture the value of time and often leads to underestimates of the elasticity of demand for fuelwood (see table 1). [4]

Similar to Cooke (1998a and 1998b), Mekonnen (1999), and Baland et al. (2010), we define the shadow price of collecting as:

$$\mu_i^C = \left(\frac{H_i^C}{q_i^C}\right)\omega_i^F \tag{25}$$

where H is the hours spent collecting per month and q is the total amount of fuelwood collected per month for household i in the collecting group C, and ω_i^F is the household level shadow wage for women.[5] Since the shadow wage is given in Kenyan Shillings per hour, the unit value of the shadow price is Kenyan shilling per kilogram (KES/Kg).

Similarly, we define the shadow price of producing fuelwood. When fuelwood is produced on-farm in SSA, it is generally as a by-product or co-product with trees existing either on marginal land or being grown for timber or pole production (Buck et al., 1999). Because production of fuelwood does not necessarily require the felling of a tree for its production, it is possible to estimate the fuelwood production potential of a farm through the number of trees that exist on the individual household's land. Doing this, and using an estimate of the time necessary to cultivate and manage an individual tree and the imputed shadow wage for men, allows us to proxy the shadow price of producing fuelwood:

$$\mu_i^P = \left(\frac{\gamma_i^P T_i^P}{q_i^P}\right)\omega_i^M \tag{26}$$

where γ is the average time needed to cultivate a tree in work months, T is the number of trees on the household's land, and q is the amount of fuelwood produced by household i in

[4]See Mekonnen (1999) for a good discussion on the subject.

[5]In this section, the subscript FW for fuelwood is dropped.

the producer group (P). The value for γ comes from the Kenya Forestry Research Institute (KEFRI) estimates for growing Eucalpytus (Oballa et al., 2010). Eucalyptus is very common in the research area and is a primary choice for agroforestry in Kenya (Scherr, 1995).[6]

Both Equations 25 and 26 require wages for men and women. Since not all households in the sample engage in off-farm wage labor,[7] we estimate the household-specific shadow wages for men and women, following the methodology proposed by Heckman (1979) and used by Cooke (1998a and 1998b) in a similar setting.[8] Results for these estimations are in table 5 in the appendix.

There are several additional aspects in our estimation strategy. First, in order to estimate cross-price elasticities, it is necessary to proxy shadow prices and market prices for households that do not participate in all groups. For example, households that only collect fuelwood off-farm do not have estimates for shadow prices for fuelwood produced on-farm or price for fuelwood bought at the market. We follow the strategy suggested by Mekonnen (1999) and use the village-specific maximum values for hours spent collecting, number of on-farm trees, and market prices, when household-specific values are absent. The household's decision to participate (or not) in each of fuelwood groups (producing on-farm, collecting off-farm, and purchasing) must reflect the household-specific cost of participation. So if the household is not observed in a particular group, it is likely the case that its cost of participation is greater than the cost of any other participating household in the village.[9]

Second, we are concerned that households may self-select into their respective fuelwood source group(s). To account for the selection bias, we add an inverse Mill's ratio following

[6]Using KEFRI's data, γ is approximately equal to 1.6 hours of work per tree over its life. 1.6 hours is equivalent to 0.01 man months, assuming eight hours in a work day and twenty days in a work month.

[7]Overall, 36.6 percent of men and 19.1 percent of women in the sample are engaged in wage labor. See also Binder and Scrogin (1999), Levison et al. (2008), and DeGraff and Levison (2009) for examples of this methodology in the development literature.

[8]We first use a probit model to estimate the likelihood of entering into the labor market for each gender to correct for selection bias. Then we include the inverse Mills ratios in a second stage OLS regression to estimate the wage rates for men and women. Our exclusion restrictions include the dependency ratio, distance from the village center, and whether there is a person in the household of the opposite gender in the workforce.

[9]One village in our sample did not have any households that purchased fuelwood. In this instance, we used the maximum price of the nearest village.

Heckman (1979) and Wooldridge (2002). Third, we take precautions against endogeneity due to the likelihood of simultaneity and omitted variable bias arising from the shadow price variable, and report results from the two-stage least squares (2SLS) estimation. We borrow an instrumental variable strategy from the demand literature, using instruments in the spirit of Hausman et al. (1994). To instrument for the market price, we use the average of all (but own) market prices in the sample. As in Hausman et al. (1994), the key assumption is that random household-level factors influencing the market price are independent from other households. As for the likely endogenous shadow prices for fuelwood collectors and producers, we match each household with five other households in the sample (outside own block[10]) based on most similar shadow price. For collectors, we use the average of the hours spent collecting of the matched households as an instrument on the shadow price of collecting of the first household, while for producers, we use the average of the number of trees as the instrument on the shadow price of producing of the first household. First stage IV results are in table 6 in the appendix.

We then estimate the monthly household-specific demand equations for fuelwood collected off-farm, q_i^C, produced on-farm, q_i^P, and bought in the market, q_i^B:

$$q_i^{j,B} = \beta_0 + \beta_1 \mu_i^j [P_i^B] + \beta_2 \nu_i^k + \beta_3 \varphi_i [\nu_i^j] + \beta_4 \omega_i^M + \beta_5 \omega_i^F + \beta_6 X_i + \theta + \varepsilon_i^{j,B} \qquad (27)$$
$$\{j, k \in \{C, P\} : \ j \neq k\}$$

where superscript j, k represents either collecting or producing, $j \neq k$, μ_i is the instrumented shadow price of either collecting or producing, ν and φ the shadow prices and market prices with full observations after Mekonnen as described above, P the instrumented market price of fuelwood, ω^M and ω^F are the average shadow wages for men and women , X_i are household variables that influence fuelwood use, θ are geographic fixed effects (at block level), and

[10] As noted earlier in the paper, a research block included three villages that were in close proximity. By excluding households in the own-block in the matching, we prevent possible validity issues arising from this geographic proximity.

φ is the error term. To avoid inflated errors due to possible automated regressor bias we bootstrap all standard errors.

5 Results

We first estimate household-specific shadow prices of collecting fuelwood off-farm and producing fuelwood on-farm, following Equations 25 and 26, and using household-specific wages for men and women. Our results, reported in Table 3 and Figure 1, confirm that fuelwood and labor markets in Western Kenya are not perfect. The median collector shadow price (1.53 KES/kg) is below the median producer shadow price (5.21 KES/kg), which is in turn below the median market price (5.85 KES/kg). This ordering is consistent with the agricultural household model that incorporates transaction costs: households neither sell nor buy a particular good if their shadow price for that good is within a "price band" determined by the transaction costs (Key et al., 2000). As the shadow prices approach and exceed the market price, households switch to purchasing from the market (given one is available). The median shadow price of fuelwood collected off-farm is also significantly below the shadow price of fuelwood produced on-farm. The large difference results from a lower opportunity cost of female labor (see Table 5). Lack of labor opportunities for women off-farm, as compared to men, suggests lower opportunity cost of female labor and depresses the shadow price of collecting fuelwood. Higher opportunity cost of male labor, as well as competition between producing fuelwood and other productive land uses such as food crop cultivation, leads to a higher shadow price of fuelwood produced on-farm.

Insert Table 3

Insert Figure 1

We then estimate demand equations (Equation 27) for different fuelwood sources, including respective shadow prices, fuelwood market price, and wages as independent variables. Table 4 shows the regression results from the ordinary least squares estimation, as well as the results from the two-stage least squares estimations that control for endogeneity of shadow prices and potential selection bias. The results across three estimations are similar. Although the tests of endongeneity and selection bias are inconclusive for both fuelwood collector and producer regressions, for the sake of caution, we use coefficient values from the 2SLS-Heckman regressions, when interpreting our results (third column for each fuelwood source group).

Insert Table 4

Coefficients on shadow prices in Table 4 can be interpreted as elasticities as all variables are used in log form. As expected, own-price elasticities are negative, inelastic, and statistically significant at the one percent level across all groups and specifications. Moreover, they are similar across fuelwood sources: own-price elasticities range from -0.575 for fuelwood collectors to -0.673 for buyers. The inelastic own-price elasticity means that increases in fuelwood cost lead to less than equal decreases in the amount of fuelwood obtained from that source, suggesting that fuelwood is a necessity good for the households in our sample. Our own-price elasticity values are also higher than elasticities found in other studies, such as Cooke, 1998a; Mekonnen, 1999; Baland et al., 2010 (table 1). Geography can play a large role in elasticity differences in fuelwood. Amacher et al. (1996) and Amacher et al. (1999), for example, find large differences in own-price elasticities between hill and plain dwelling populations in Nepal. Most of existing studies on this subject are primarily from South Asia, and none are from samples in Kenya or in the Lake Victoria basin in general.

Cross-price elasticities are also inelastic, but positive, and are only statistically significant for fuelwood producers.[11] The very low cross-price elasticities suggest that substitution between fuelwood sources is low. Although fuelwood is often considered to be a homogeneous product, households in Western Kenya have strong preferences for particular fuelwood

[11]This is likely an outcome of a small sample size for collectors and buyers of fuelwood. If the sample sizes for these groups were similar to fuelwood producers, we believe that all the cross- price elasticities would be statistically significant.

sources and do not readily substitute between them. An increase of one percent in the shadow price of producing (corresponding to an increase of 0.14 KES/kg), for example, leads to a decrease in fuelwood produced of 2.63 kg per month at the mean. At the same time, substitution to a different source is low: the increase of fuelwood both bought and collected is only 0.40 kg per month at the mean. The one percent increase in the producer shadow price therefore leads to a net decrease of 2.23 kg per month in fuelwood consumed, holding other fuelwood costs constant.

In terms of income elasticities of demand for different fuelwood sources, we find similar patterns as those observed in the descriptive statistics. Although we do not include household income as an independent variable due to endogeneity concerns, the coefficient on a wealth index that aggregates household assets is positive and significant for producers and buyers, and negative (though insignificant) for collectors (Table 4). For the households in our sample, fuelwood produced on-farm and bought are normal goods, while fuelwood collected off-farm is an inferior good, further confirming source differentiation.

The lack of substitution between fuelwood sources can be also partly explained by the gender division in household labor. We find that female wages in the demand equations are statistically significant with respect to fuelwood collected, and male wages are likewise statistically significant with respect to fuelwood produced (Table 4). The coefficients in both cases are positive, similar to findings in other studies (Skoufias, 1994; Amacher et al., 1996; Cooke, 1998a; Amacher et al., 1999), and provide evidence of an upward-sloping labor supply curve for fuelwood: As increasing amounts of labor are used for obtaining fuelwood, the implicit wage for fuelwood collection or production increases.

This result also lends support to our claim that fuelwood tasks in Kenya are still segregated by gender, as is shown by the qualitative work from the 1980s (Chavangi and Adoyo 1993). We also see that increases in the shadow price of collecting have significant increases on the amount of female labor spent gathering fuelwood off-farm. Using the same 2SLS regression as above (Equation 27) but with the amount of hours spent collecting per month as the dependent variable, we find that a one percent increase in the shadow price of collecting increases the hours spent collecting by 0.42 percent (not included in table).[12] Evaluated at the mean of 13.5 collecting hours in the sample, a ten percent increase in the shadow price of collecting increases the time spent collecting by 0.54 hours per month for women. This percent increase in labor expended is greater in magnitude than the combined cross-price elasticities of collecting with producing and buying fuelwood (0.159), illustrating that households prefer to increase labor for a source rather than substitute to another.

A small increase in the shadow price can therefore have potentially large effects on the labor burden of household women and negatively affect well-being. The fact that women in the developing world are often responsible both for household and "productive" tasks such as fuelwood collection create a "double workday" and longer effective working hours than their male counterparts (Blackden and Wodon, 2006; Kes and Swaminathan, 2006). Thus, increases in the shadow prices of collecting can potentially lengthen this already demanding working day for women in the developing countries.

6 Conclusion and Policy Implications

Assuming fuelwood markets are imperfect and household production and consumptions decisions are non-separable, we extend the agricultural household model to focus on the substitution between different fuelwood sources – produced on-farm, collected off-farm, and purchases – and on the role of household's labor endowment. Using the household-level data from the Western Kenya highlands, we estimate the demand equations for different fuelwood sources, including respective shadow prices, fuelwood market price, and wages as independent variables and controlling for potential selection bias and endogeneity.

We find that the median household shadow price of collecting (1.5 Kenyan shillings per kilogram (KES/kg)) is well below the median shadow price of producing (5.2 KES/kg) and median market price (5.8 KES/kg). Lack of off-farm labor opportunities for women as com-

[12] Palmer and MacGregor (2009) find a 0.04 percent increase in labor supplied, while Cooke (1998a) finds a value of 1.02 percent (see table 1).

pared to men depresses the shadow price of collecting, while competition of agroforestry with on farm crops among other factors increases the shadow price of producing. We find that female wages in the demand equations are statistically significant with respect to fuelwood collected and male wages are likewise statistically significant with respect to fuelwood produced. This finding suggests strict labor divisions between men and women and confirms the earlier findings from the qualitative studies in western Kenya showing strong social and cultural norms that women are primary collectors of fuelwood off-farm and men are primary producers on-farm (Chavangi and Adoyo, 1993).

Looking specifically at fuelwood collected, we find that the own-price elasticity (-0.575 to -0.673) is greater than the labor elasticity (.42), which is greater than the combined cross-price elasticities for collected fuelwood with produced and purchased fuelwood. Together, our findings confirm that fuelwood is strongly differentiated based on its source. Moreover, the rural Kenyan households prefer to increase female labor of collecting fuelwood rather than substitute to other fuelwood sources.

Few prior studies have analyzed substitution between fuelwood sources, implicitly assuming that fuelwood is a homogeneous resource. The lack of substitution as suggested by our results, however, implies that increases in the shadow price of fuelwood from any particular source can potentially have significant effects on households, especially with regard to labor, and suggests several policy implications. In the long run, increasing off-farm labor opportunities for women could lead to higher shadow price of collecting fuelwood and increase fuelwood from other sources. As producing fuelwood on-farm, for example, is more sustainable than collecting off-farm, this could lead to increased tree coverage and other associated benefits. In the short run, however, given very limited substitution between fuelwood collected and produced, any increases in the shadow price of collecting are likely to increase work burden for women. Policy priorities, therefore, need to focus on increasing substitution between fuelwood sources, which implies increasing labor substitutability between genders.

Our analysis also suggests the strong linkages between women's well-being and environmental well-being. Increasing gender equality not only addresses concerns for the quality of life for women in these areas, but could also serve to increase substitution between fuelwood sources. The increased substitution could lead to increases in on-farm tree coverage, thus addressing environmental sustainability and offsetting emissions associated with burning of biomass. Therefore, reforestation efforts in western Kenya may be ineffective unless there are changes to traditional norms regarding female participation in on-farm tree management and the off-farm labor market. These norms appear to be gradually changing however: The new Kenyan constitution, approved by a significant majority of Kenyan citizens in 2010 codifies new rights for women in society, including the ability to own and inherit land (Kramon and Posner, 2011). This appears to be evidence of a shift in norms in Kenyan society favoring equality between men and women. Over the upcoming years, these changing norms may lead to increasing substitution between male and female labor. This study indicates that if this does occur, the result may be increases in agroforestry, tree coverage, and the associated environmental benefits.

References

Acharya, G. and E. Barbier (2002), 'Using Domestic Water Analysis to Value Groundwater Recharge in the Hadejia-Jama'are Floodplain, Northern Nigeria', *American Journal of Agricultural Economics*, **84**(2): 415–426.

Amacher, G.S., W.F. Hyde, and B.R. Joshee (1993), 'Joint production and consumption in traditional households: Fuelwood and Crop Residues in Two Districts in Nepal', *Journal of Development Studies* **30**(1): 206–225.

Amacher, G.S., W.F. Hyde, and K.R. Kanel (1996), 'Household fuelwood demand and supply in Nepal's tarai and mid-hills: Choice between cash outlays and labor opportunity', *World Development* **24**(11): 1725–1736.

Amacher, G.S., W.F. Hyde, and K.R. Kanel (1999), 'Nepali Fuelwood Production and Consumption: Regional and Household Distinctions, Substitution and Successful Intervention', *Journal of Development Studies* **35**(4): 138–163.

Baccini, A., S.J. Goetz, W. S. Walker, N. T. Laporte, M. Sun, D. Sulla-Menashe, et al. (2012), 'Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps', *Nature Climate Change* **2**(3): 182–185.

Bailis, R., M. Ezzati, and D. M. Kammen (2005), 'Mortality and greenhouse gas impacts of biomass and petroleum energy futures in Africa', *Science* **308**(5718): 98–103.

Baland, J.M., P. Bardhan, S. Das, D. Mookherjee, and R. Sarkar (2010). 'The Environmental Impact of Poverty: Evidence from Firewood Collection in Rural Nepal', *Economic Development and Cultural Change* **59**(1): 23–61.

Berazneva, J., J. Conrad, D. Güereña, J. Lehmann (2015). 'Agricultural productivity and soil carbon dynamics: a bioeconomic model', Ph.D. thesis, Cornell University, Ithaca, NY.

Binder, M. and D. Scrogin (1999). 'Labor Force Participation and Household Work of Urban Schoolchildren in Mexico: Characteristics and Consequences', *Economic Development and Cultural Change* **48**(1): 123–154.

Blackden, C. and Q. Wodon (2006), 'Gender, Time Use, and Poverty: Introduction', in C. Blackden and Q. Wodon (eds.), *Gender, Time Use, and Poverty in Sub-Saharan Africa*, Washington D.C.: The World Bank, pp. 1-12.

Bradley, P. N. and M. Huby (1993), *Woodfuel, Women and Woodlots*, Washington D.C.: The World Bank

Buck, L. E., J. P. Lassoie, E. Fernandes (1999), *Agroforestry in Sustainable Agricultural Systems*, Washington D.C.: CRC Press

Chavangi N. and F. Adoyo (1993), 'Towards an Extension Strategy', in P.N. Bradley and M. Huby (eds.), *Woodfuel, Women and Woodlots, Volume 2: The Kenya Woodfuel Development Programme*, London and Basingstoke: Stockholm Environment Institute, pp. 58-73.

Cooke, P. A. (1998a), 'Intrahousehold Labor Allocation Responses to Environmental Good Scarcity: A Case Study from the Hills of Nepal', *Economic Development and Cultural Change* **46**(4): 807–830.

Cooke, P. A. (1998b), 'The Effect of Environmental Good Scarcity on Own-Farm Labor Allocation: The Case of Agricultural Households in Rural Nepal', *Environment and Development Economics* **3**(4): 443–469.

Crafford, R., P. Munoz, T. De Oliveira, C. Lambrechts, M. Wilkinson, A. Burger, and J. Bosch (2012), 'The Role and Contribution of Montane Forests and Related Ecosystem Services to the Kenyan Economy', UNEP

DeGraff, D. S. and D. Levison (2009), 'Children's Work and Mothers' Work–What is the Connection?' *World Development* **37**(9): 1569–1587.

Food and Agriculture Organization: UN (2010), 'Deforestation and Net Forest Area Change', http://www.fao.org/forestry/30515/en

Hausman, J., G. Leonard, and J. D. Zona (1994), 'Competitive Analysis with Differenciated Products', *Annales d'Economie et de Statistique* **34**(2): 159–180.

Heckman, J. (1979). 'Sample Selection Bias as a Specification Error', *Econometrica* **47**(1): 153–161.

Heltberg, R., T. C. Arndt, T. and N.U. Sekhar (2000), 'Fuelwood Consumption and Forest Degredation: A Household Model for Domestic Energy Substitution in Rural India', *Land Economics* **76**(5): 213–232.

Hosonuma, N., M. Herold, V. De Sy, R. S. De Fries, M. Brockhaus, L. Verchot, A. Angelsen, and E. Romijn (2012), 'An assessment of deforestation and forest degradation drivers in developing countries', *Environmental Research Letters* **7**(4): 1-12.

International Energy Agency (2014), *Africa Energy Outlook: Executive Summary*, https://www.worldenergyoutlook.org/africa

Jacoby, H. G. (1993), 'Shadow Wages and Peasant Family Labor Supply: An Econometric Application to the Peruvian Sierra', *The Review of Economic Studies* **60**(4): 903–921.

Joint Research Center: The European Commission (2013), 'Deforestation rates in Africa slowed down by 50%', https://ec.europa.eu/jrc/en/news/deforestation-rates-africa-slowed-down-50-9929

Kenya Forest Service (2009), 'A Guide to On-Farm Eucalyptus Growing in Kenya'

Kes, A. and H. Swaminathan (2006), 'Gender and Time Poverty in Sub-Saharan Africa', in C. Blackden and Q. Wodon (eds.), *Gender, Time Use, and Poverty in Sub-Saharan Africa*, Washington D.C.: The World Bank, pp. 13-38.

Key, N., E. Sadoulet, and A. de Janvry (2000), 'Transactions Costs and Agricultural Household Supply Response', *American Journal of Agricultural Economics* **82**(2): 245–259.

Kramon, E., and D. N. Posner (2011), 'Kenya's New Constitution', *Journal of Democracy* **22**(2): 0–21.

Levison, D., K. S. Moe, and F. Knaul (2008), 'Marking Time: An Analysis of Youth Hours of Work and Study in Urban Mexico', *Review of Development Economics* **12**(4): 751–763.

Lin, H., M. Ezzati, and M. Murray (2007), 'Tobacco Smoke, Indoor Air Pollution and Tuberculosis: A Systematic Review and Meta-Analysis', *PLOS Medicine* **4**(1)

Maathai, W. (2003), *The Green Belt Movement: Sharing the Approach and the Experience*, Lantern Books

Mathu, W. (2011), 'Forest Plantations and Woodlots in Kenya', African Forest Forum Working Paper Series.

Mekonnen, A. (1999), 'Rural Household Biomass Fuel Production and Consumption in Ethiopia: A Case Study', *Journal of Forest Economics*, **5**(1): 69-97.

Oballa, P. O., Konuche, P. K. A., Muchiri, M. N., and B. N. Kigomo (2010). 'Facts on Growing and Use of Eucalyptus in Kenya', Nairobi: Kenya Forestry Research Institute

Palmer, C. and J. MacGregor (2009), 'Fuelwood Scarcity, Energy Substitution, and Rural Livelihoods in Namibia', *Environment and Development Economics* **14**(6): 693-715.

Pattanayak, S.K., E.O. Sills, and R.A. Kramer (2004), 'Seeing the Forest for the Fuel', *Environment and Development Economics* **9**(2): 155–179.

Republic of Kenya: Ministry of Environment, Water, and Natural Resources (2014), 'Forest Policy 2014'

Scherr, S. J. (1995), 'Economic Factors in Farmer Adoption of Agroforestry: Patterns Observed in Western Kenya', *World Development* **23**(5): 787-804.

Simonit, S. and C. Perrings (2011), 'Sustainability and the value of the 'regulating' services: Wetlands and water quality in Lake Victoria', *Ecological Economics* **70**: 1189–1199.

Singh, I., L. Squire, and J. Strauss (1986), 'Methodological Issues', in I. Singh, L. Squire, J.Strauss (eds.), *Agricultural Household Models*, Baltimore: Johns Hopkins University Press, pp. 48-70.

Skoufias, E. (1994), 'Using Shadow Wages to Estimate Labor Supply of Agricultural Households', *American Journal of Agricultural Economics* **76**(2): 215-227

Strauss, J., (1986), 'The Theory and Comparative Statics', in I. Singh, L. Squire, J. Strauss (eds.), *Agricultural Household Models*, Baltimore: Johns Hopkins University Press, pp. 71–91.

Wilson and Spracklen, (2009). Forest loss and restoration – a case study of tropical montane forest Roger Wilson, World Land Trust Dominick Spracklen, University of Leeds.

World Meteorological Organization, (2005) *Climate and Land Degradation*, WMO-No. 989. Geneva, Switzerland.

World Wide Fund for Nature (WWF), (2007) *Dirty Thirty: Ranking of the most polluting power plants in Europe*, Brussels, Belgium.

Wooldridge, J. (2002), *Econometric Analysis of Cross Section and Panel Data*, Cambridge, MA: The MIT Press.

Yasuoka, J. and R. Levins, (2007), 'Impact of deforestation and agricultural development on Anopheline ecology and malaria epidemiology', *American Journal of Tropical Medicine and Hygiene*, **76**(3): 450–460

Zhou, G., S. Munga, N. Minakawa, A. K. Githeko, and G. Yan, (2007), 'Spatial Relationship between Adult Malaria Vector Abundance and Environmental Factors in Western Kenya Highlands', *American Journal of Tropical Medicine and Hygiene* **77**(1): 29–35

Appendix

Figure 1:

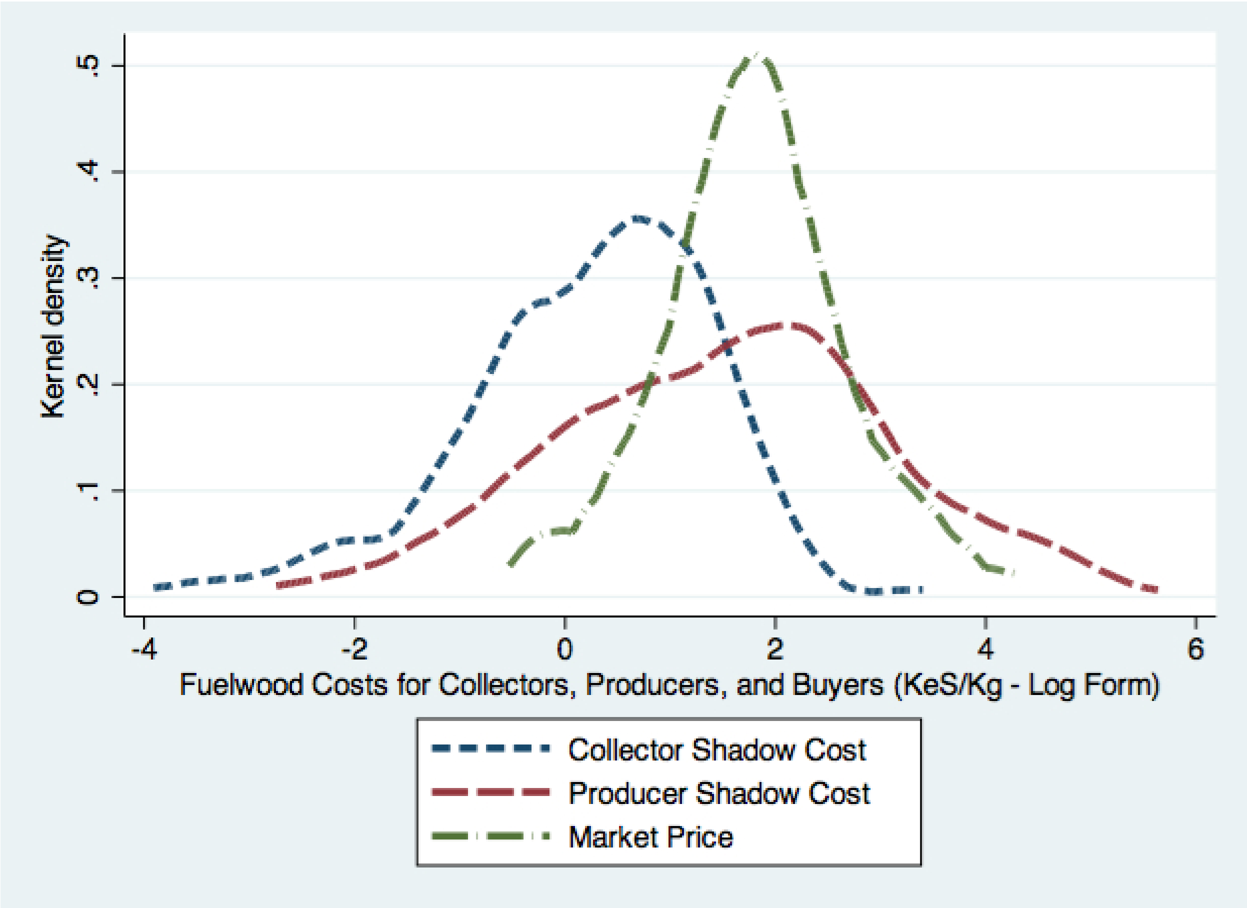

Table 1: Literature Fuelwood Elasticities

Paper	Variable (Per-Unit)	Demand Elasticity (Own-Price)		N	Labor Elasticity (Total Collection Time)		N	Location
Amacher et al. (1993)	Collection Time	-0.157	*	89				Nepal
Amacher et al. (1996)†	Market Price	-1.69/-.59	***/-	286/240	.82/.97	***/*	286/240	Nepal
Cooke (1998a)	Shadow Cost	-0.25	***	101	1.02	**	101	Nepal
Mekonnen (1999)	Shadow Cost	-0.40	***	419				Ethiopia
Amacher et al. (1999)†	Market Price	-.21/-1.47	*/*	286/240				Nepal
Heltberg et al. (2000)	Collection Time	-0.11	*	178	0.89	*	176	India
Palmer and MacGregor (2009)	Collection Time	-0.05	*	172	0.04	***	172	Namibia
Baland et al. (2010)	Shadow Cost	-.134	*	2190				Nepal

† These papers provide elasticity estimates for two distinct populations and do not provide a combined estimate.
*** p<0.01, ** p<0.05, * p<0.1, - not statistically significant. All variables are per unit measures.

Table 2: Summary Statistics

VARIABLES	Collectors	Non-Collectors	Difference	Producers	Non-Producers	Difference	Buyers	Non-Buyers	Difference
Household Income	104,684	145,662	-40,978**	123,861	144,446	-20,585	148,905	116,862	32,043*
	(8,237)	(11,249)	(17,051)	(9,233)	(19,414)	(21,607)	(15,600)	(10,467)	(17,894)
Off-Farm Income Ratio	0.63	0.54	0.092**	0.55	0.69	-0.14***	0.58	0.58	0.000080
	(0.029)	(0.027)	(0.041)	(0.023)	(0.046)	(0.051)	(0.035)	(0.025)	(0.043)
Remittence Income Ratio	0.094	0.10	-0.0076	0.10	0.087	0.014	0.12	0.089	0.028
	(0.019)	(0.017)	(0.025)	(0.014)	(0.028)	(0.032)	(0.024)	(0.015)	(0.026)
Imp. Monthly Female Wage	2,259	2,497	-237	2,421	2,276	145	2,638	2,266	372**
	(102)	(99.9)	(151)	(86.0)	(172)	(191)	(143)	(92.1)	(157)
Imp. Monthly Male Wage	2,208	2,228	-20.8	2,240	2,131	109	2,470	2,089	382***
	(101)	(91.1)	(138)	(74.8)	(156)	(173)	(127)	(83.4)	(143)
Off-farm Emp. (% Men)	0.56	0.48	0.081	0.48	0.66	-0.18**	0.57	0.48	0.093
	(0.044)	(0.038)	(0.058)	(0.032)	(0.065)	(0.073)	(0.049)	(0.036)	(0.061)
Off-farm Emp. (% Women)	0.32	0.28	0.038	0.28	0.40	-0.12*	0.30	0.30	0.0030
	(0.041)	(0.035)	(0.053)	(0.029)	(0.060)	(0.067)	(0.045)	(0.033)	(0.056)
HHH Sex	0.82	0.79	0.030	0.82	0.74	0.082	0.83	0.80	0.027
	(0.033)	(0.030)	(0.046)	(0.025)	(0.052)	(0.058)	(0.038)	(0.028)	(0.048)
HHH Age	48.6	54.0	-5.38***	52.2	49.2	2.97	51.3	51.8	-0.56
	(1.37)	(1.16)	(1.75)	(0.94)	(2.01)	(2.23)	(1.51)	(1.09)	(1.86)
Number of Children	5.98	5.99	-0.011	6.01	5.86	0.15	6.40	5.77	0.63
	(0.30)	(0.26)	(0.39)	(0.22)	(0.45)	(0.50)	(0.35)	(0.24)	(0.41)
% Women in Household	0.498	0.52	-0.032	0.51	0.47	0.038	0.51	0.50	0.015
	(0.016)	(0.016)	(0.024)	(0.014)	(0.028)	(0.031)	(0.020)	(0.015)	(0.026)
Household Size	6.36	5.84	0.52*	6.03	6.21	-0.17	6.75	5.71	1.04***
	(0.19)	(0.19)	(0.28)	(0.16)	(0.32)	(0.36)	(0.25)	(0.17)	(0.29)
HHH Years of Education	6.69	6.54	0.16	6.77	5.91	0.86	7.23	6.28	0.96*
	(0.34)	(0.34)	(0.51)	(0.28)	(0.58)	(0.64)	(0.44)	(0.31)	(0.53)
Number of Trees	114	144	-29.1*	140	94.5	45.1**	131	131	-0.58
	(11.2)	(9.86)	(15.0)	(8.61)	(16.8)	(18.7)	(13.2)	(9.20)	(15.7)
Herd Size	1.99	2.69	-0.69**	2.58	1.54	1.04***	2.22	2.47	-0.24
	(0.21)	(0.21)	(0.31)	(0.18)	(0.35)	(0.39)	(0.23)	(0.19)	(0.33)
Land Area (Acres)	2.72	5.93	-3.21***	5.08	2.27	2.80*	2.67	5.50	-2.83**
	(0.25)	(0.75)	(1.14)	(0.70)	(1.30)	(1.45)	(0.22)	(0.70)	(1.20)
Wealth Index	-0.23	0.12	-0.35***	0.0021	-0.17	0.17	0.16	-0.13	0.30***
	(0.052)	(0.071)	(0.11)	(0.062)	(0.12)	(0.14)	(0.096)	(0.066)	(0.11)
Km. from Village Center	0.36	0.46	-0.099***	0.43	0.36	0.075	0.39	0.43	-0.043
	(0.022)	(0.024)	(0.037)	(0.022)	(0.042)	(0.047)	(0.025)	(0.023)	(0.039)
Observations	131	173		243	61		103	201	

Standard errors located below respective means. HHH=Household Head. Total sample is 301 observations. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 3: Fuelwood Cost and Quantity Statistics

Variable	Obs	Median	Mean	Std. Dev.	Min	Max	Unit
Market Price	103	5.85	9.02	10.64	0.59	73.10	KeS/Kg
Producer Shadow Price	243	5.21	13.91	28.31	0.06	280.27	KeS/Kg
Collector Shadow Price	131	1.53	2.21	3.01	0.02	30.01	KeS/Kg
Fuelwood Bought	103	120.0	326.59	773.59	5.0	5700.0	Kg
Fuelwood Produced	243	160.0	431.81	1274.73	3.4	17989.2	Kg
Fuelwood Collected	131	80.0	160.69	224.53	1.0	1600.0	Kg

Note: Statistics are for households who participate in the particular fuelwood source group.

Table 4: Main Results

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
VARIABLES	Fuelwood Collected (Monthly)			Fuelwood Produced (Monthly)			Fuelwood Bought (Monthly)		
	OLS	2SLS	2SLS+Heckman	OLS	2SLS	2SLS+Heckman	OLS	2SLS	2SLS+Heckman
Shadow Price Collecting	-0.571***	-0.567***	-0.575***						
	(0.107)	(0.162)	(0.172)						
Shadow Price Producing				-0.591***	-0.612***	-0.610***			
				(0.0480)	(0.0736)	(0.0737)			
Market Price							-0.861***	-0.706***	-0.673***
							(0.115)	(0.115)	(0.123)
Shadow Price Collecting (Full)				0.0559***	0.0555***	0.0501**	0.0771***	0.0737**	0.0344
				(0.0179)	(0.0186)	(0.0226)	(0.0292)	(0.0298)	(0.0348)
Shadow Price Producing (Full)	0.0696	0.0691	0.0969				0.0595	0.0515	0.173**
	(0.0474)	(0.0521)	(0.0759)				(0.0521)	(0.0564)	(0.0795)
Market Price (Full)	0.0823	0.0821	0.0624	0.155***	0.155***	0.148**			
	(0.105)	(0.109)	(0.116)	(0.0598)	(0.0596)	(0.0662)			
Female Wage	0.842***	0.838**	0.868**	-0.202	-0.206	-0.214	0.226	0.236	-0.0520
	(0.299)	(0.330)	(0.350)	(0.165)	(0.174)	(0.167)	(0.372)	(0.380)	(0.394)
Male Wage	-0.0840	-0.0838	-0.128	0.841***	0.862***	0.834***	-0.0287	0.00154	0.194
	(0.183)	(0.191)	(0.225)	(0.156)	(0.176)	(0.188)	(0.271)	(0.270)	(0.277)
HH Controls, Block Dummies	√	√	√	√	√	√	√	√	√
Kleibergen-Paap rk LM P-value		0.0000	0.0000		0.0000	0.0000		0.0002	0.0001
Kleibergen-Paap rk Wald F stat		26.288	26.469		58.361	58.113		26.469	26.076
Stock-Yogo 10% maximal IV size		16.38	16.38		16.38	16.38		16.38	16.38
Hausman Test P-value		0.9763	0.9730		0.6844	0.6959		0.0090	0.0092
Lambda coefficient			0.310			-0.174			1.728**
			(0.597)			(0.385)			(0.761)
Constant	-2.112	-2.087	-2.263	-0.976	-1.078	-0.727	3.166	2.613	0.800
	(2.229)	(2.451)	(2.517)	(1.347)	(1.341)	(1.497)	(2.297)	(2.520)	(2.445)
Observations	131	131	131	243	243	243	103	103	103
R-squared	0.408	0.408	0.410	0.608	0.607	0.608	0.520	0.509	0.532

All variables are in log form. Explanations for "full" variables and IVs provided in text. All regressions bootstrapped with 1000 repetitions. Standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 5: Wage Regressions

	Male			Female		
	OLS	MLE Heckman		OLS	MLE Heckman	
VARIABLES	Male Monthly Wages		Selection	Female Monthly Wages		Selection
Years of education	0.0772***	0.0617***	-0.00739	0.106***	0.103***	0.00981
	(0.0150)	(0.0168)	(0.0192)	(0.0234)	(0.0209)	(0.0220)
Age	0.0778***	0.162***	0.218***	-0.0148	0.0277	0.182***
	(0.0239)	(0.0287)	(0.0236)	(0.0225)	(0.0435)	(0.0296)
Age squared	-0.000807***	-0.00180***	-0.00251***	0.000368	-0.000157	-0.00220***
	(0.000296)	(0.000350)	(0.000288)	(0.000277)	(0.000548)	(0.000387)
Herd size in TLU	0.0554***	0.0218	-0.0732***	0.0461	0.0414	-0.0171
	(0.0205)	(0.0244)	(0.0267)	(0.0332)	(0.0320)	(0.0320)
Dependence Ratio			-0.190**			0.144*
			(0.0804)			(0.0852)
Distance in Km from Village Center			-0.442**			-1.230***
			(0.205)			(0.322)
Female Labor Participation			0.287**			
			(0.122)			
Male Labor Participation						0.275*
						(0.149)
Village Dummies	√	√	√	√	√	√
Clustered SE at Household Level	√			√		
Rho			0.8617***			0.4544
			(0.0801)			(0.2675)
Sigma			0.8204***			0.6835***
			(0.0847)			(0.0860)
Lambda			0.7069***			0.3106
			(0.1340)			(0.2166)
LR Test P-Value			0.0024***			0.1725
Constant	6.058***	3.927***	-3.687***	7.032***	5.757***	-4.178***
	(0.480)	(0.627)	(0.535)	(0.570)	(1.144)	(0.670)
Observations	202	536	536	105	540	540
R-squared	0.432			0.436		

Heteroskedastic-Robust Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. All dependent variables are in log form.

Table 6: First Stage IV Regressions

VARIABLES	(1) Shadow Price of Collecting	(2) Shadow Price of Producing	(3) Market Price
Shadow Price of Collecting (Full)		-0.0151	-0.0109
		(0.0244)	(0.0184)
Shadow Price of Producing (Full)	0.145***		0.0456
	(0.0534)		(0.0294)
Market Price (Full)	0.0112	0.0594	
	(0.0979)	(0.0786)	
Hours Collect (IV)	0.0848***		
	(0.0145)		
Number of Trees (IV)		0.0122***	
		(0.00125)	
Except-own Mean Mkt Price (IV)			-59.98***
			(14.65)
Monthly Female Wage	0.746***	-0.0919	-0.0283
	(0.237)	(0.231)	(0.219)
Monthly Male Wage	0.0349	0.694***	-0.0832
	(0.188)	(0.204)	(0.169)
HH Controls, Block Dummies	√	√	√
Constant	-7.315***	-4.989***	134.4***
	(1.759)	(1.766)	(32.43)
Observations	131	243	103
R-squared	0.501	0.509	0.676

All variables in log form. Explanations for "full" variables and IVs provided in text. All regressions bootstrapped with 1000 repetitions. Standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.