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On the Adoption and Dis-adoption of Household Energy and Farm Technologies

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To My Wife and My Parents

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Abstracts

This thesis consists of four self-contained papers.

Paper I: Intra-household bargaining power and demand for clean and energy efficient stoves: Experimental evidence from rural Ethiopia

Clean and energy efficient stoves improve the well-being of rural households by reducing fuel consumption, fuel collection time and the adverse health impact of indoor air pollution. However, the demand for such stoves is surprisingly low in rural areas of many less-developed countries. A real stove purchase experiment is conducted in Ethiopia to study the role of intra-household bargaining power in explaining the observed low demand for improved stoves. Using the Becker-DeGroot-Marschak method, we find a significant effect of intra-household bargaining power on improved stove adoption. However, a follow-up survey conducted long after the stove distribution shows that bargaining power does not affect how quickly the new stove was put into use. Our findings show the importance of empowering women in order to increase adoption in rural improved stove programs.

JEL Classification: Q40, D1, Q50

Key Words: Improved stove, Willingness to pay, Autonomy (power), Ethiopia

Paper II: Disadoption, substitutability and complementarity of agricultural technologies: A random effects multivariate probit analysis

In this paper, we analyze what drives farmers to disadopt green revolution technologies (inorganic fertilizer and improved seed) and whether the disadoption of green revolution technologies is related to adoption/non-adoption of other sustainable land management practices (such as farmyard manure and soil and water conservation practices). Random effects multivariate probit regression results based on rich plot level data suggest that black/brown soil type, flatter slope, shorter distance to homestead and extension centers, and access to water are negatively correlated with disadoption of green revolution agricultural technologies. Further, we find that the disadoption of green revolution technologies is related to the non-adoption of other sustainable land management practices. Our results strengthen previous findings of complementarity between green revolution technologies and sustainable land management practices by showing that the latter can reduce the likelihood of disadoption of green revolution inputs.

JEL Classification: Q01, Q12, Q16, Q18

Key Words: Adoption, disadoption, agriculture, technology, multivariate probit, Ethiopia

Paper III: Household fuel choice in urban China: Evidence from panel data

Using seven rounds of household survey data that span more than a decade, this paper analyzes the determinants of household fuel choice in urban China. Using a correlated random effects generalized ordered probit model, we find that household fuel choice in urban China is related to fuel prices, household's economic status and size, and household head's gender and education. Our results suggest that policies and interventions that reduce prices of clean fuel sources and empower women in the household are of great significance in encouraging the use of clean energy sources.

JEL Classification: C25, Q23, Q40, Q42

Key Words: Household fuel choice; Panel data; Random effects generalized probit model; Urban China

Paper IV: Adoption and disadoption of electric cookstoves in urban Ethiopia: Evidence from panel data

Previous studies on improved cookstove adoption in developing countries use cross-sectional data, which make it difficult to control for unobserved heterogeneity or to investigate what happens to adoption over time. We use robust non-linear panel data and hazard models on three rounds of panel data from urban Ethiopia to investigate the determinants of adoption and disadoption of electric cookstoves over time. We find that the prices of electricity and firewood and access to credit are major determinants of adoption and transition. Our findings have important implications for policies aiming to promote energy transition and to reduce the pressure on forest resources in developing countries.

JEL Classification: Q40, Q41, Q42, Q48

Key Words: Cookstoves; Electric Mitad; Firewood; Panel data; Random effects probit

Overview

Most households in developing countries use biomass fuels with inefficient stoves to meet their cooking needs. In addition, agriculture in these countries is characterized by low productivity. Hence, technical advances in energy efficiency and agricultural methods are crucial to enhance welfare related to these essential consumption and production activities.

Burning of biomass fuels with inefficient stoves has health and environmental impacts. Inefficient biomass cookstoves emit a large amount of smoke, which creates indoor air pollution in the kitchen. The World Health Organization (WHO, 2009) estimates that around 2 million deaths per year are directly attributable to indoor air pollution from the use of biomass fuels. This means that indoor air pollution associated with biomass use is directly responsible for more deaths than malaria (International Energy Agency, 2010). Further, the inefficient use of biomass fuels depletes resources and degrades local environments, multiplies the time needed to collect fuel –time that could have been used in other productive activities. There is also mounting evidence that biomass burned inefficiently contributes to climate change at regional and global levels (Lewis and Pattanayak, 2012).

One key solution is to use clean energy sources such as electricity or liquefied natural gas (LNG). However, transition toward widespread use of these clean energy sources is slow in many developing countries. It is particularly slow in rural areas because most of them do not have access to these clean energy sources and depend on freely available biomass fuels. Hence, for rural households, transition to clean and energy-efficient biomass stoves (improved biomass stoves) can be of immediate and significant benefit. However, previous efforts to promote the use of these technologies in rural areas of many developing countries were not successful. This could be due to institutional constraints, poor quality improved stoves, households'reluctance to adopt them, etc. (El Tayeb Muneer and Mukhtar, 2003; World Bank, 2011; Lewis and Pattanayak, 2012; Alem et al., 2014). In recent years, with increased concern about climate change, there is a renewed interest in promoting a new generation of improved biomass cooking stoves that are well designed, affordable and burn fuel cleanly and efficiently (World Bank, 2011). Promotion of these technologies has been included in the energy policy of some countries (e.g., Ethiopia). However, the adoption of these new generation improved stoves is surprisingly low. We investigate this low demand in depth in **Paper I**, taking rural Ethiopia as a case study.

In the rural areas of the least-developed countries, women and children, who are traditionally responsible for cooking and fuelwood collection, are the primary victims of diseases related to indoor air pollution and of the time-consuming and exhausting task of fuelwood collection (Pitt et al., 2006). Hence, the benefits of adopting these improved stoves mainly accrue to women and children. However, in these countries, large proportions of women (wives) do not have a say in how household income is spent. As a result, improved stoves may not be on the household's priority list of items for investment. In **Paper I**, we hypothesize that, controlling for other factors, the low household demand for improved stoves in rural Africa may reflect husbands'low preference for the stove and/or wives'low autonomy in decisions that affect their utility. However, once the stove is acquired, either by purchasing it or getting it for free from government or NGOs, we expect no difference in how quickly the new stove is put to use by wives, whether they have high or low bargaining power.

To test the above hypotheses, a real stove purchase experiment and follow-up survey were conducted in randomly selected villages of the Southern Tigrai region of Ethiopia. Representative husbands and wives (acting individually) and couples (acting jointly) were randomly selected to participate in a Becker-DeGroot-Marschak (BDM) experiment. The joint preference is introduced to represent "the household level demand"and individual preferences are used to represent the individual preferences of husbands and wives. Our results indicate that there is no significant difference between husbands'preference and joint (household) preference, while a significant difference is found between wives'preference and joint (household) preference. Further, we find a negative and significant relationship between husbands'bargaining power and their preference for the improved stove, while there is a positive and significant relationship between wives' bargaining power and their preference for the improved stove. Results from a follow-up survey show that there is no significant difference in how quickly the new stove was taken into use among wives with high, medium and low bargaining power, i.e., if a stove is obtained, all women have equal incentive and opportunity to use it regardless of their power. Therefore, in patriarchal societies, such as in rural households in Ethiopia in particular, and in Africa in general, these results explain, at least partly, the coincidence of the observed low household demand for improved stoves and women's low bargaining power.

Beyond these energy-related problems, a large proportion of rural households in the sub-Saharan African (SSA) countries are food insecure. The main reason for this is low agricultural productivity. Improving agricultural productivity in SSA is essential in tackling the region's food security issues as water and land resources become increasingly limited. Since the success story of the Asian green revolution, there have been hopes that green revolution technologies (improved seed and inorganic fertilizer) would solve food insecurity in sub-Saharan Africa. However, there has not been a significant increase in crop productivity, and food insecurity (undernourishment) has declined by only an insignificant amount (O'Gorman, 2006; Teklewold et al., 2013). One reason could be the low rate of adoption of green revolution technologies. Another reason could be farmers'disadoption of these technologies. One reason for disadoption of these technologies is that farmers may have been supplied the same type of technologies without testing the differing nutrient requirements and acidity of their soil. In In **Paper II**, we seek to know what drives farmers to disadopt these green revolution technologies and whether the disadoption of green revolution technologies is related to adoption/non-adoption of other sustainable land management practices (such as soil conservation practices, farmyard manure).

We find that farmers who use green revolution technologies in plots with black/brown soil type are less likely to disadopt the technologies. This result is in line with agronomy findings that black/brown soil has relatively higher organic components and higher water holding capacity. Water holding capacity and organic components of soil are important elements to facilitate decomposition and to normalize acidity and release nutrients when green revolution technology is applied to the soil. Our results show that farmers who use the mix of green revolution technologies and other land management practices are less likely to disadopt the green revolution technologies. Farmers who use a green revolution technology (fertilizer) without applying other sustainable land management practices are also more likely to disadopt the green revolution technology, which is consistent with previous findings regarding complementarity between these practices.

Paper III and **IV** return to the problem of household fuel choices and examine urban households' fuel and energy technology transition in China and Ethiopia. Unlike rural households, urban households have relatively better access to clean energy sources and depend on purchased fuel sources (i.e., they may have the ability to pay the monthly bill for these clean energy sources). Hence, for these households, the transition to improved biomass stoves that is discussed in **Paper I** may not be optimal. By transitioning to clean energy sources (i.e., not biomass), these households can avoid indoor air pollution and may also save money because the cost per kilo Joule of useful energy may be cheaper if clean energy is used compared to biomass fuels. For example, in Ethiopia, the cost per kilo Joule of useful energy from electricity is cheaper than that from fuelwood and charcoal (own computation using data from CSA, 2011). Despite these benefits, urban households'transition to clean energy sources is slow and some households exit from (disadopt) these clean energy sources.

In **Paper III** we use seven rounds of panel data from the China Health and Nutrition Survey (CHNS), one of the most widely-used surveys for micro-level research in China, to study determinants of urban households'cooking fuel choice over long periods of time. In the past two or more decades, there has been an increasing trend in the number of urban households in China that have transitioned from biomass fuels, such firewood and coal, to clean energy, such as liquefied natural gas (LNG) or electricity (the CHNS 1989-2006 survey). Understanding the determinants of the transition in urban China will be helpful in finding ways to accelerate the transition to cleaner fuels in developing countries generally.

Most previous studies that investigate household fuel choice are based on cross-sectional data, and the previous studies in urban China are mainly based on aggregate statistics or on surveys conducted in certain province or counties (e.g., Wang and Feng, 1997; Farsi el al., 2007, Chen et al., 2006). To our knowledge, no study has examined household energy choices in China through panel data from a nationwide household survey. This paper tries to fill this gap by using seven-round panel data from the CHNS. Further, we make two extensions to the application of an ordered discrete choice model to the fuel choice issue. First, this paper employs a more flexible empirical framework through generalized ordered probit models, rather than the standard ordered probit model, which is based on a restrictive assumption of the parallel regression. Second, to explore the panel structure of the data set, the random effects generalized ordered probit model with Mundlak transformation was adopted to analyze the household fuel choices.

Our results indicate the heterogeneous effects of the explanatory variables across the distribution of different cooking fuels, which supports the use of the generalized ordered probit model. Further, the results indicate that interventions that reduce the price of clean energy (LNG) can encourage households to use it as the primary cooking fuel and reduce the usage of dirty fuel sources. In addition, we find that households with female heads are more likely to transition to LNG as the primary cooking fuel, which implies that greater empowerment of women in the household can be helpful in increasing the usage of clean energy in urban China. More education for household heads is also highly likely to increase the transition of households to LNG. Our results also show a significant reduction of fuelwood consumption over time. This may be related to the introduction of more restrictive forest policies, such as the Natural Forest Conservation Program, which was introduced in 1998 (Zhang et al., 2000).

In **Paper III**, we studied the transition to clean fuel without focusing on the appliance that enables households to start using clean energy. In fact, the transition to clean energy is conditioned on the acquisition of an appropriate cooking appliance, which often requires substantial financial outlay by poor households. Even after purchase of a clean stove, some households have discontinued using it. The reason for discontinuance could be difficulty in replacing the stove once it wore out, or the need to resell the stove to cope with economic shocks. In **Paper IV**, we analyze what drives households to continue or discontinue using clean stoves. We use robust non-linear panel data and hazard models and a broad set of explanatory variables to answer this question.

Our results show that prices of electricity and firewood are important determinants of adoption and disadoption of electric stoves. This result supports the idea that raising the price of biomass fuel (for example, by introducing a tax) and reducing the price of electricity (for example, through a carefully-designed subsidy or reduction in the average price of electricity through investment in hydroelectric power production) would have a positive impact on continued adoption. This could be more effective if combined with interventions that improve access to credit, which is also found to be a significant determinant of adoption, such as micro-finance support. This is important since the urban poor lack the financial capacity to meet the start-up cost of acquiring modern cooking appliances. In addition, socio-economic characteristics of other household members (other than head) such as education and labor market status of female members are also important determinants of continued adoption of the stove, which indicates the trickle-down effects of factors such as education and labor market status within the household. This finding brings us back to the role of empowering women in order to achieve desirable energy consumption outcomes.

To sum up, this thesis examines determinants of adoption and disadoption of clean household energy and improved agricultural technologies in developing countries. The empirical findings from this study add to the literature on household energy transition and continued use of improved agricultural technologies in developing countries. For example, understanding gender-based differences in preferences and intra-household bargaining power in the rural setting of developing countries is important for widespread adoption of improved cookstoves. Prices of clean fuels and technologies are also found to be important determinants of transition to clean energy sources. Because poor households represents a large share of the population in developing countries, a carefully-designed subsidy or reduction in the average price would assist the transition to clean energy sources. Last but not least, in order for farmers to continue using green revolution technologies, they need to mix them with other sustainable land management practices. For the application of inorganic fertilizer to be more sustainable, greater care should be given to the nutrient requirements and acidity of the soils.

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Paper I

Intra-household bargaining power and demand for clean and energy efficient stoves: Experimental evidence from rural Ethiopia.*

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Abstract

Clean and energy efficient stoves improve the well-being of rural households by reducing fuel consumption, fuel collection time and the adverse health impact of indoor air pollution. However, the demand for such stoves is surprisingly low in rural areas of many less-developed countries. A real stove purchase experiment is conducted in Ethiopia to study the role of intra-household bargaining power in explaining the observed low demand for improved stoves. Using the Becker-DeGroot-Marschak method, we find a significant effect of intra-household bargaining power on improved stove adoption. However, a follow-up survey conducted long after the stove distribution shows that bargaining power does not affect how quickly the new stove was put into use. Our findings show the importance of empowering women in order to increase adoption in rural improved stove programs.

JEL Classification: Q40, D1, Q50

Key Words: Improved stove, Willingness to pay, Autonomy (power), Ethiopia

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1 Introduction

The transition from inefficient traditional biomass cookstoves to more energy efficient and clean cookstoves is one of the major sustainability challenges facing developing countries. Substantial resources have been devoted to promoting clean and energy efficient stoves in these countries (Mobarak et al., 2012). However, the adoption and use of these stoves is low and several aspects of adoption remain poorly understood. The existing articles on improved stove adoption have documented the following reasons for low adoption: lack of knowledge about the benefits of the stove, low level of formal education, inability to pay the full cost of the stove, lack of access to credit, supply constraints, and institutional constraints and problems related to the stoves (El Tayeb and Mukhtar, 2003; Edwards and Langpap, 2005; Beyene and Koch, 2012; Jan, 2012; Alem et al., 2014). In this study, we look into less-studied factors: differences in decision-making autonomy (power) and preferences within the household.

Clean and energy efficient stoves improve the well-being of rural households by reducing fuel consumption, fuel collection time and the health impact of indoor air pollution. The benefits of adopting these improved stoves accrue mainly to women and children, who are traditionally responsible for cooking and fuelwood collection (Barnes et al., 1994; El Tayeb and Mukhtar, 2003; Pitt et al., 2006). For example, in the study area, only 16% of men in the sample participate in fuelwood collection, as opposed to 81% of the women. Due to their long hours in kitchens with traditional cookstoves that emit a large amount of smoke, women are the primary victims of diseases related to indoor air pollution (Pitt et al., 2006).[1] On the other hand, in rural Africa, men are mostly the default household head and control the household's cash accounts (El Tayeb and Mukhtar, 2003; Kishor and Subaiya, 2008; Khlin et al, 2011). Large proportions of women do not have a say in how household income is spent. Improved stoves may not be on the household's priority list of items for investment, as the default (male) household head, who is not mainly responsible for cooking and fuelwood collection, may not fully consider the cost of unclean and inefficient

[1]Pitt et al. (2006) pointed out that, in rural Bangladesh, although women are generally responsible for cooking, not all female household members do the cooking. In their study, they find that wives and daughters-in-law spend more time cooking than do other women in the household, who are primarily daughters of the head. The finding that wives are more responsible for cooking is in line with the context in the study area and the hypothesis to be tested in this study.

traditional cookstoves to other household members who are responsible for those tasks. Therefore, we hypothesize that, controlling for other factors, the low household demand for improved stoves in rural Africa may reflect husbands' low preferences for the stove and/or wives' low autonomy in decisions that affect their utility. In other words, other things being held constant, the transition from dirty and inefficient cookstoves to relatively clean and efficient cookstoves will depend on the autonomy of women in the household. However, once the stove is acquired, we expect no difference in the use of the stove among wives with high and low bargaining power; i.e., all wives will use it regardless of their bargaining power

Almost all rural households in Ethiopia use traditional energy sources such as fuelwood from communal and private lands (Beyene, 2012). Such a high level of dependence on non-market biomass fuel implies that rural households' transition to alternative, purchased fuel sources such as electricity or kerosene is less likely in the short run and that biomass will continue to be a dominant energy source in the short and medium term. Heavy dependence on these fuel sources is associated with high depletion of the forest resources in the country and is expected to rise with population growth (Beyene, 2012). Forests that covered 16% of the highlands in the 1950s have shrunk to less than 3% at present and the rising consumption of firewood plays a crucial part in this (Berry, 2003).

To mitigate the adverse consequences of inefficient biomass consumption by rural households in Ethiopia, a transition to biomass fuel-saving technologies is among the most promising short and medium term solutions. However, previous efforts to promote the use of improved stoves in the country were not successful, in part due to problems related to institutions and in part due to households' reluctance to adopt and use the stoves (Gebreegziabher et al., 2006). In recent years, with growing awareness of climate change, there is a renewed interest in promotion of a new generation of improved cooking stoves. Promotion of these technologies has been included in the country's growth and transformation plan (Tigrai Regional Bureau of Planning and Finance, 2011). Therefore, understanding the link between technology adoption and intra-household gender dynamics will be an important input for successful promotion and use of these fuel-saving technologies.

This paper uses data from a real stove purchase experiment in six villages of southern Tigrai region, Ethiopia, where representative husbands, wives and joint couples were randomly selected to participate in the experiment. The Becker-DeGroot-Marschak (BDM) experiment method (Becker et al., 1964) is used to reveal subjects'preferences (by stating their maximum willingness to pay (WTP)) for the clean and fuel-saving stove. The BDM design is incentive compatible because subjects make real trade-offs when making decisions (Hoffmann, 2009). We prefer this method instead of just asking the subjects to buy the stove at a predetermined price because we want to know the strength of the preference difference between husband and wife. Moreover, we also want to know how valuable improved stoves are to rural households. Such knowledge may help us learn the amount of subsidies that are needed if improved stove dissemination programs are not feasible at full cost.

In the experiment, the joint preference (expressed by the couple) is introduced to represent "the household level demand "and individual preferences are used to represent the individual preferences of husbands and wives. Preferences revealed in this way may enable us to see to what extent "the household level demand "resembles the husband 's or the wife's preferences. However, their individual/joint preferences may still be confounded by their decision-making autonomy (power) in the household. For example, a wife who has low decision-making autonomy (power) in the household may state low WTP in the individual decision, not because she does not like the new stove, but because she may know that her husband will not approve of such a purchase. Thus, a low-power wife will report what her husband prefers to have. Therefore, for a patriarchal society, ignoring the intra-household power relation may mislead us to the conclusion that husbands and wives have the same preferences for the stove.

In addition to the experiment on joint and individual preference, we use a survey-based measure of spouses'decision-making autonomy (power). This direct measure is derived from survey questions wherein husbands and wives are asked separately either he or she has "the final say "in some household decisions, such as the decision over the purchase of household durable items and of items for wives'material needs. The death of male siblings of the spouses and the spouses'birth order are used as instruments to measure autonomy (power). As explained in the latter sections, a wife with a large number of adult male siblings is more likely to be protected and respected in her house and community. A shock to this variable is highly likely to affect the power of the wife in the house and community. Moreover, due to specific cultural conditions of the study area, a wife with the lowest birth order (i.e., the first-born female in her family) is likely to have more assets under her control because she is likely to get more assets for marriage. These two instruments do not affect stove purchase decisions directly except through decision-making power

Empirical evidence on the effect of intra-household decision-making autonomy and preference differences on the adoption and use of clean and energy efficient technologies is rare. However, there exist some empirical studies that look at the role of gender in the decision to adopt these technologies (Dutta, 1997; Cecelski and Unit, 2000; El Tayeb and Mukhtar; 2003; Troncoso et al., 2007; Alem et al., 2014). Nonetheless, most of these are based on a qualitative approach and on observational data. Moreover, they do not look at intra-household power and preference differences *per se*, and their empirical strategies do not allow for inferring a causal relationship between the explanatory variables and adoption. However, recently Miller and Mobarak (2013) studied gender differences in preferences based on an experimental approach in rural Bangladesh. They also made an indirect inference about women's power by comparing those who were asked to pay for a stove with those who were given the stove for free. The current study builds on Miller and Mobarak (2013) but is different in four ways. First, we estimate the effect of power (autonomy) more directly, using both experimental and survey methods. Second, the BDM design may also be better for measuring the strength of the preference difference between husbands and wives. This design also gives a better measurement of how valuable improved stoves are to rural households in general. Third, using follow-up survey data, we estimate the effect of intra-household bargaining power on the actual use of the stove. Fourth, as the evidence on this aspect of stove transition is very thin in developing countries, our study adds evidence from Africa on whether the transitions from dirty and inefficient stoves to clean and efficient stoves have been constrained by intra-household decision-making autonomy and preference differences.

We find that wives are generally willing to pay 60% more than husbands for an improved stove. Moreover, wives who make the decision individually are willing to pay 40% more than those who make the decision together with their husbands. However, there is no significant difference between husbands who make the decision individually and jointly. Wives who have high and moderate autonomy in decisions regarding the purchases of the household's durable items and their own material needs are willing to pay more than two times that of husbands who are autocratic (one who does not involve his wife in decisions) and moderate (one who involves his wife in decisions). Bargaining power is observed to have an impact on the purchase of the stove. For a patriarchal society, such as rural Ethiopia, the result explains the coincidence of low observed household demand for improved stoves and husbands'very low preferences for the stove. On the other hand, the results from a follow-up survey conducted long after the stove distribution shows that there is no significant difference in the use of the stove among wives with high, medium and low bargaining power. These findings imply that rural improved stove programs may not be successful if we ignore these power imbalances and the low demand expressed by husbands

The rest of paper is organized as follows: section two introduces the experimental design and procedure. In sections three , we provide a simple model on intra-household bargaining power and demand for improved stoves. Section four discuses the empirical strategy of our study. Sections five and six present the descriptive statistics and econometric results, respectively. Finally, the last section concludes.

2 Experimental Setting, Data Collection and Design

Choice of geographical location

The experiment was conducted in the southern Tigrai region, Ethiopia. The region contains the "Dega", "Weynadega"and "Kola "agro-ecological zones.[2] These are the major agro-ecological conditions of the country. It is also a region where some households have relatively high access to fuelwood, while others have low access. In the areas with low access to fuelwood, households have to travel on average around 30 km to collect fuelwood, but only 6 km in areas with relatively high fuelwood access. Having such a variation in climate and forest conditions provides a favorable opportunity for the stove purchase experiment because the demand for stoves may vary depending on the weather and access to fuelwood.

Improved stoves have been introduced in Ethiopia in general and the Tigrai regional state in particular since the 1980s. Different government and non-government institutions have been involved in the development and dissemination of several types of biomass cookstove technologies (Gebreegziabher et al., 2006). However, the efforts made by these institutions to disseminate various types of improved stoves have not been very successful, partly due to problems related to the stove itself (some of the stoves were not really improved or were easily broken) and partly due to households'reluctance to adopt the stoves. Unlike the old

[2]Kola , at an altitude between 500 and 1500 meters above sea level (m.a.s.l), is characterized by a relatively hotter and drier climate, whereas Weynadega (15002500 m.a.s.l) and Dega (25003500 m a.s.l) are wetter and cooler (Desersa et al. 2010).

generation of improved stoves that were used in previous programs, the new stoves have quality control assurance during the manufacturing process, use energy more efficiently and pay attention to combustion efficiency (Gebreegziabher et al., 2006; Tigrai Regional Bureau of Planning and Finance, 2011). Even with such improvements in efficiency and quality, the adoption rate is disappointingly low. For example, in the Tigrai regional state, the take-up of the new generation biomass stove (Mirte stove) is less than 1% (Tigrai Regional Bureau of Planning and Finance, 2011).

Data collection

A baseline and follow-up survey was conducted in randomly selected 12 villages (kushets) in the region that represents these major weather and forest conditions.[3] For the baseline survey, a total of 600 sample households were randomly selected from these villages. A total of 300 married subjects[4] were used for the stove purchase experiment from six villages where the new generation improved stove (Mirte stove) had not been introduced.[5] The remaining 300 households were selected from six other villages which will be used for an impact assessment study that involves a free distribution of stoves. We randomly selected 50 households from each village using a list of households obtained from each villages administrator. In villages with free distribution of stoves, 25 households from each village are treatments (i.e., those who received the free stove) and the remaining 25 are controls. However, in the villages where we conducted the stove purchase experiment, all 50 subjects from each village participated in the experiment.

We conducted a baseline survey two weeks before the stove purchase experiment and free distribution of the improved stoves. The survey was conducted using a group of 15 enumerators, one supervisor and seven village cadres. In these villages, after the village cadres 'and enumerators'short introduction about the study, both husband and wife were asked if they were willing to be interviewed. If both agreed, the village cadre left and the interview started. Fortunately, both spouses were available and volunteered to be interviewed.[6] We

[3]The baseline survey was conducted in July-October, 2013 and the follow-up survey was done January-February, 2015

[4]Subject here means either husband only, wife only or couples acting jointly

[5]Old generation stoves were made of mud and were not marketable. Households were trained to build the stoves using freely available inputs: soil and stone.

[6]Two weeks before we conducted the baseline survey, the village leader and village cadres received a

conducted the survey one village at a time, i.e., all 15 enumerators interviewed all 50 subjects in most villages, except in two villages, where 48 and 49 households were interviewed.[7] On average, the survey questions took 1.45 hours per household. In the survey, households were asked about their socio-economic characteristics, fuel use, cooking practices, awareness about adverse consequences of cooking with traditional stoves, awareness about improved cookstoves, household decision-making power, etc.

A year and a half after the baseline survey, a follow-up survey was also conducted for all households that participated in the baseline survey.[8] Most of the survey questions in the follow-up survey were the same as in the baseline survey, except that we added questions that captured stove use in the follow-up.

In villages where the stove purchase experiment was conducted, 10 representative husbands, 10 representative wives and 30 joint couples from each village were randomly invited to participate in the experiment. We informed these subjects that they were randomly selected to come to the farmers'training center on a specified date for two to four hours of compensated physical work (weeding) and two more hours participating in a study. All those randomly selected were willing to come and participate in the physical work and experiment. The physical work was introduced to ensure that farmers would buy the improved stove using income earned from this work.

Conducting an experiment with real labor income has the advantage of demonstrating to what extent households in the study area can commit to purchase decisions using income obtained in exchange for labor. This is important because almost all households in the study area depend on earned income (mainly agricultural income). We want to make the experiment as realistic as possible and there is a risk that subjects might treat windfall income and earned income differently in the decision to buy the stove. This is in line with the theory of mental accounting which stipulates that consumers tend to arrange expenditures into separate mental accounts and how the money is spent depends on how it is acquired

list of married households selected for the survey. The cadres and leaders asked couples if they would be available at the time we planned to conduct the survey in the village. If they would not be available, the cadres were told to replace them with the next neighbor. However, we did not do the replacement, as all said they would be available.

[7]Three households in these villages were neither available at home nor on the appointed dates.

[8]One household was not asked to participate in the follow-up survey because it had migrated to a different region

(Thaler, 1999; Hoffmann, 2009; Clingingsmith, 2015). Proponents of the theory of mental accounting argue that income earned in exchange for labor is treated differently than income from windfall (Thaler, 1999; Clingingsmith, 2015). Christiaensen and Pan (2012) discussed the notion of 'Easy come, easy go'which is common in many societies around the world (including the study area). They discussed this notion as "the money that is earned more easily is spent more easily, as exemplified by the expression that 'Easy come, easy go ', an expression, which finds its counterpart across the world's languages, 'Lai de rong yi, qu de kuai'(Chinese),and 'Bekelalu Yemta Bekalau Yehedal '(Amharic, Ethiopia)"(Christiaensen and Pan, 2012). Christiaensen and Pan (2012) found evidence of this notion in rural China and Tanzania. Further, Thaler (1999) and Clingingsmith (2015) documented that subjects are likely to share less from an earned dollar than from a windfall dollar (Thaler, 1999; Clingingsmith, 2015). Earned income and windfall income can thus be considered different mental accounts. Christiaensen and Pan (2012) found that farmers in China and Tanzania tend to spend earned income on necessity goods/services while windfall income is spent on alcohol and other luxury items.

Before the invited subjects arrived at the place of our stove experiment, the subjects did not know anything about the stove purchase and purpose of the experiment. This was done to avoid information spread, pre-experiment spousal influence and self-selection in attending the experiment. In the survey, subjects were informed that the purpose of the survey would be to study socio-economic conditions of households in Tigrai, that their village had been selected randomly for this study and that they were also selected randomly from the village. Likewise, in the villages where we conducted free distribution, the stoves were not given out during the baseline survey. In these villages, before we started the interview, the village cadre informed households that they would be given a gift after two weeks at the farmers training center, without specifying the type of the gift.

Experiment design and procedures

The stove purchase experiment was conducted in three steps. First, subjects were asked to work at the weeding activity for four hours. Second, farmers were given a demonstration of the new attributes of the improved stove and training on how to assemble and disassemble the stove. Finally, they did the stove purchase experiment in five groups. In what follows, we explain these steps.

In cooperation with the administrators of the farmers'training centers, village leaders and village cadres that were involved in the baseline survey, we organized farmers to arrive at the place of the experiment at different time schedules. Representative husbands/wives who were invited to come alone were told to arrive at 7 a.m. On the other hand, representative joint couples were told to arrive at 9 a.m. In the two weeks before the experiment, village leaders and village cadres reminded the subjects that, if they arrived late, they would be excluded from the list of those who would participate in the compensated work.[9] All representative husbands/wives arrived by 8:00 a.m. and representative joint couples by 10:00 a.m.[10] Upon arrival, the representative husbands/wives were told that they would weed for four hours per person in the center plots and stay two hours more for a study, while the representative joint couples were told that they would each weed for two hours per person and stay two hours more for a study. It was required for both partners to work for these hours. They were also informed that, at the end of the study, remuneration would be paid in proportion to the time invested. A representative husband/wife who participated alone would earn ETB 150[11] , while a couple who worked together would get also ETB150.[12] We also told them that it was not possible to choose only one of the two activities (either weeding or participating in the experiment). No payment would be given if they did not participate in both activities. Fortunately, no subject rejected participating in both activities nor asked to participate in only one of the activities.

After completing the weeding activity, we gathered all the subjects (50 subjects) in one place and gave them a demonstration of the attributes of the new cooking stove. In the demonstration, the experimenter explained the fuel saving, smoke reduction, time saving, life span and other attributes of the new cooking stove. The same demonstrator was used

[9]They were also informed that there would not be any payment to be given and they would be excluded from participation if delayed.

[10]I.e., there was a one hour delay in both groups.

[11]The daily wage rate in the region for weeding was between 90 and130 ETB (Ethiopian birr) (4.78- 6.90 USD), excluding other benefits. These benefits include food and drinks. If the food and drink expenses were included the wage, it would be around 150 ETB (7.96 USD), so the wage we paid is neither overestimated nor underestimated. If we include the travel time to the farmers training center (on average 1 hour for a single trip), they spent 8 hours of their time for the study. The exchange rate during the study period was 1 USD= 18.85ETB.

[12]It is common for households in the study area to work in soil conservation, tree planting and other activities in public areas with similar payments sponsored by other non-governmental organizations.

in all villages to avoid the effect of the demonstrator (see Appendix C for the statements used in the experiment). Once the demonstration was done, we divided the subjects into five groups and placed them in separate places that were far apart. The groups were: a group of representative husbands who were invited alone and would make the stove purchase experiment alone using the income they earned individually; a group of representative wives who were invited alone and would make the stove purchase experiment alone using the income they earned individually; a group of husbands who were invited with their wives and would make the stove purchase experiment alone using the income the couple earned; a group of wives who were invited with their husbands and would make the stove purchase experiment alone using the income the couple earned; and a group of joint couples who would make the stove purchase decision jointly using the income the couple earned. Figure 1 of Appendix A presents a summary of the above group types and number of subjects in each of these five categories.

"Figure 1 here"

In these groups, we had subjects who made decisions individually using individually earned income, while others decided individually using jointly earned income. We include these income types to see to what extent husbands and wives treat individually earned income and "household"(joint) income differently in the purchase decisions. With this approach, we can test the argument in the intra-household literature that women in the rural households of Africa have limited access to the household (joint) income to make material purchases for themselves and their children (Kishor and Subaiya, 2008; Orfei, 2012).

Under the above procedures, it would be in the best interest of the participants to bid according to their actual valuation of the improved stove. We explained to participants that, if they stated an amount higher than the maximum they actually want to pay, they would be forced to pay it if that price was randomly chosen. On the other hand, if they bid a price below their actual willingness to pay and a higher price was drawn, they would not be allowed to buy, even if they wanted to buy it at this randomly drawn price. To avoid the effect of the experimenter, one experimenter explained the mechanism of the BDM for each group in all villages. A subject participating in the stove purchase experiment might ask about the need to state his/her/their maximum WTP instead of just asking him/her/them to pay a price. Before the subjects could raise such questions, we gave an explanation using the following statement:

"You might wonder why we ask you to give a bid for the stove instead of just asking you to pay a price. Well, this research tries to establish how valuable such improved stoves are to you. We would therefore ask you to think carefully about the most you would be willing to pay for the stove. (See Appendix C for the details of the script of the experiment)

Before they started the actual biding for the improved stove, we did a practice experiment using a pencil. We took two different pencils of different quality. One is an improvement over the other. The standard pencil is made with wooden material, standard lead and a standard eraser, while the improved one is made of plastic material, high quality lead and a quality eraser. The improved one is better in terms of strength of the lead during use and cleanliness of the paper after using the eraser. In the experiment, all were familiar with the standard pencil, but did not know about the other pencil. We asked them the maximum price they were willing to pay for the improved pencil. This practice experiment was done in each group.

To make the bids for the stove as confidential as possible, subjects were placed as far apart as possible; we instructed subjects to keep their bids confidential; and we directed them not to talk to each other or ask questions in public, from the beginning to the end. If they had questions, we asked them to raise their hands and the experimenter would give answers privately. At the end, all groups were called back to one place and a subject among them would pick a price from a bucket containing the stated prices.

3 Conceptual Framework

In this section, we provide a conceptual framework of willingness to pay for clean and energy efficient stoves in the context of intra-household differences in preferences; the relationship of these differences to the decision-making autonomy (power) of the randomly selected representative husbands and wives who make the purchase decisions individually; and the implications for spouses who make the decision jointly. We build this simple model of individual subjects'elicitation of their preference for the improved stove based on Larson and Rosen (2002), Pattanayak and Pfaff (2009) and Miller and Mobarak (2013).

When subjects adopt and use clean and fuel-saving improved stoves, this can induce a welfare change, due to time savings from fuel collection and lower emissions of indoor air pollutants. The demand for such interventions is derived from their willingness to pay to obtain the welfare increase associated with adopting and using such interventions (Larson and Rosen, 2002). In making decisions, consumers decide whether to pay the retail price (p) for such interventions based on their willingness to pay, i.e., a consumer buys the item if

$$WTP - p \geq 0 \tag{1}$$

On the basis of equation (1), in what follows we model the relationship between power and WTP and how this power may differently affect the elicitation of husband's and wife 's WTP, and we discuss the assumptions used to establish the relationship.

Let WTP_w^* and WTP_h^* be wife's and husband's latent willingness to pay that does not include the influence of a spouse. Let WTP_w and WTP_h be observed willingness to pay during the experiment. This may or may not include spousal influence, depending on each spouse's decision-making power in the household. Further, let p be the price of the improved stove and $(\alpha_w\ , \alpha_h) \in [0, 1]$ be the wife's and husband's decision-making power in the household, respectively. For simplicity, assume discrete power 0 and 1 (low and high power). Thus, $\alpha_w + \alpha_h = 1$. Further assume that cooking and fuel collection are the wife's responsibility.

A wife who made the stove purchase decision in the absence of her husband might face a punishment D_w at home if she purchased the stove and the husband did not like it. Suppose the punishment is implemented at a probability of $1 - \alpha_w$ provided that her husband does not like it. However, the husband who made the stove purchase decision in the absence of his wife might be punished D_h if he does not buy the improved stove, given the assumption that cooking and fuel collection are the wife's responsibilities. Suppose also the punishment for a low-power husband is implemented at a probability of $1 - \alpha_h$.

If we ignore the spousal influence i.e., if individuals make the purchase decision according to their individual true valuation the wife will buy the improved stove if:

$$WTP_w^* - p \geq 0 \tag{2}$$

Her net benefit or payoff from the purchase is $WTP_w^* - p$. The husband will buy if:

$$WTP_h^* - p \geq 0 \tag{3}$$

His net benefit or payoff from the purchase is $WTP_h^* - p$. However, as discussed above, a wife will face a punishment of D_w at a probability of $1 - \alpha_w$ if her husband does not like the purchase. The husband will not like the purchase if $WTP_h^* - p < 0$. Nevertheless, if the husband's and wife's preferences match, the wife will not face the punishment even if she has low power. The probability that the husband likes her purchase is:

$$\phi^h(WTP_h^* - p \geq 0) = 1 - \Phi^h(p) \tag{4}$$

where Φ^h and ϕ^h are cumulative and density probability functions of the husband's latent willingness to pay. Therefore, a wife participating in the experiment will purchase the improved stove if her expected payoff is greater than or equal to zero, i.e.:

$$E[payoff]_w = (1-\Phi^h(p))[(WTP_w^*-p)]+\Phi^h(p)[\alpha_w(WTP_w^*-p)+(1-\alpha_w)(WTP_w^*-p-D_w)] \geq 0 \tag{5}$$

$$= WTP_w^* - (1 - \alpha_w)\Phi^h(p)D_w - p \geq 0 \tag{6}$$

Using equations (2) and (6), the observed willingness to pay of a wife who makes the decision in the absence of her husband is given by

$$WTP_w = WTP_w^* - (1 - \alpha_w)\Phi^h(p)D_w \tag{7}$$

From (7), we can see that a wife's observed willingness to pay and her latent willingness to pay will diverge if she has no autonomy in the house and she will reveal a preference that will have high acceptance by the husband, which implicitly means that she will reveal her husband's preference (willingness to pay).

For the husband who makes the decision individually in the absence of the wife, he will face the punishment D_h at a probability of $1 - \alpha_h$ if he does not buy the improved stove, provided that he is a low-power husband. The low-power husband will add D_h into his willingness to pay. Therefore, a husband will buy the stove if his expected payoff is greater than or equal to zero, i.e.:

$$E[payoff]_h = (1 - \alpha_h)[WTP_h^* + D_h - p] + \alpha_h[WTP_h^* - p] \geq 0 \tag{8}$$

$$= WTP_h^* + (1 - \alpha_h)D_h - p \geq 0 \tag{9}$$

Using equations (3) and (9), the husband's observed willingness to pay is given by

$$WTP_h = WTP_h^* + (1 - \alpha_h)D_h \tag{10}$$

From (10), we can also see that the observed willingness to pay of a husband is negatively related to his power. If the wife is powerful enough, his preference will converge to his wife's preference. For the spouses who make the decision jointly in the experiment, the observed willingness to pay will reveal either the husband's or wife's latent preference, depending on their bargaining power.

4 Empirical strategy

Alternative approaches have been used in the empirical literature to estimate the impact of intra-household power on various household outcomes. One approach is to use indirect measures of power from survey data, such as an individual member's asset ownership, income share or education, and link this measurement to observed household outcome. In this approach, a woman/man with a higher share of assets or income in the household is assumed to have high decision-making power. The most frequent income and asset types used in the literature are unearned income such as transfers (Schultz, 1990; Thomas, 1990; Duflo, 2003), inherited assets (Quisumbing, 1994), assets brought into marriage (Quisumbing and Briere, 2000) and current assets (Quisumbing and Briere, 2000).

The problem with the above approach is that it does not directly show how individual preferences affect household decisions because individual and household (joint) preferences are not separately observed, i.e., we cannot know whether the observed choice of a member is taken at her/his own preference or at the behest of the other spouse. Moreover, these indirect proxy measures are subject to selection and omitted variable biases. Some authors have used a randomized experiment or quasi-randomized experiment to eliminate selection and other biases (e.g., Duflo, 2003).

Another survey-based approach is to use "direct evidence of power "of members and correlate it with observed household outcome. In this regard, husband and wife are asked survey questions about whether he or she has "the final say "about specific or multidimensional household decisions (Becker et al., 2006; Freidberg and Webb, 2006; Allendorf, 2007; Mabsout, 2010; Chakraborty and De, 2011). In this approach, individual preferences are assumed to be reflected in the observed household choices where the individual has high decision-making power. This approach directly observes the decision-making, and some authors prefer the use of this measure instead of making inferences from indirect measures of power (Friedberg and Webb, 2006; Mabsout, 2010; Chakraborty and De, 2011). This direct indicator may also be subject to omitted variable biases. However, this bias can also be removed by using some exogenous instruments. For example, Chakraborty and De (2011) have used distance to natal family as an exogenous instrument of this direct measure of power.

The final approach is to use an experimental approach and estimate the influence of individual decisions on household (joint) decisions (de Palma et al., 2011; Carlsson et al., 2012; Yang and Carlsson, 2012; Carlsson et al., 2013). The advantage of this approach is that both individual members preferences and their joint (household level) decisions are observed. This means it is possible to directly estimate to what extent household (joint) decisions are influenced by individual spouse preferences (decision). Carlsson et al. (2012, 2013) and Yang and Carlsson (2012) have used this approach to estimate the spousal influence on risk and time preferences of Chinese households. However, this spousal influence estimate is not causal because elicitation of the preferences in the individual decision can be affected by the unobserved decision-making power of the subjects in the house and other confounding factors. Despite this, it is a preferred method because it uses both individual and joint choices of the same household, which are difficult to get using the survey method.

In the framework of a contingent valuation method, Whittington et al. (2008) and Prabhu (2010) also used separate interview method for husbands and wives to study subjects WTP for HIV and malaria vaccines in Thailand and India, respectively. Unlike Whittington et al. (2008), Prabhu (2009) has also interviewed husbands and wives jointly to elicit their individual WTP.[13] As stated in Whittington et al. (2008), preference studies based on a contingent valuation method may suffer from “yea saying, ”i.e., respondents may say “yes ”to valuation questions with the aim of pleasing the interviewer or for other reasons. Further, as stated in the above paragraph, their preferences in the individual decision can also be affected by the unobserved decision-making power of the subjects in the house and other confounding factors.

In this study, in the spirit of the method used in Carlsson et al. (2012, 2013), we design an experiment by taking representative husbands, wives and joint couples from different

[13] Even though Prabhu (2009) interviewed husband and wife jointly, the author did not ask one aggregate WTP from the joint interview. After letting husband wife to discuss, the author asked individual WTP in the joint decision, which makes it difficult to take this as single a joint WTP.

households to participate in the stove purchase experiment.[14] As long as these representative husbands, wives and joint couples are selected randomly, we can take their preferences as a substitute for the individual and joint preferences of the same household.[15] By comparing individual husband and wife preferences with the preferences of joint couples, we can infer the influence of husband/wife. However, revelation of preferences in individual decisions may be confounded by their decision-making autonomy (power) in the household. We control and estimate the effect of this by using a survey-based direct measure of autonomy (power).

Because the survey-based measure of power is endogenous due to measurement error and/or unobserved factors, we used two instruments to address these concerns. Taking advantage of circumstances and cultural conditions of the study area, we used birth order of couples and death of male siblings of the spouse as exogenous instruments of the bargaining power of the couples, in particular wives'power. In rural parts of the Southern Tigrai region, the study area, land is one of the assets that couples bring to marriage. Couples get this land from their parents; the amount of land brought to the marriage depends on their birth order. A wife/husband who is first in birth order is more likely to get married earlier and get more land from her parents than a wife/husband with a later birth order. Upon separation, the husband/wife does not have a claim on this land because legally it is registered in the name of the wife's/husband's parents.[16] In addition to this, a wife who is first in birth order is likely to get more assets at marriage, as elder siblings are more respected and parents are likely to receive more gifts from friends and relatives in the marriage party of their

[14]Husbands and wives in the individual decision groups are not from the same household. They are randomly chosen from different households. Likewise, husbands/wives in the individual decision groups are not from the same household as those in the joint decisions. However, husbands and wives in the joint decision are from the same household. This means we do not have husbands and wives from same household participating in both joint and individual decisions because such a design could result in one household buying more than one improved stove. In the study area, households use the improved stove to prepare the main Ethiopian staple food (injera) on average twice a week and a household does not need to have more than one improved stove.

[15]Randomization of subjects into joint and individual decisions will be tested by checking whether there exists any significant difference in socio-economic characteristics of the subjects participating in these two decisions.

[16]Other siblings of the spouses do not have a claim on marriage gifts after parents die. These gifts become common knowledge and the law recognizes them.

elder daughter/son. Therefore, a wife who is first in birth order is more likely to have more assets under her control and hence more power than a wife with the last birth order. This instrument is exogenous and not directly related to stove purchase decisions, except through bargaining power.

The second instrument, death of male siblings of spouses, is related to the influence of natal kin on the position of women in the household and community. Borrowing from sociological and anthropological literature consistent with circumstances in the study area, a wife with more adult male siblings is more likely to be protected and respected and to get material support than a wife who has more female siblings (Dyson and Moore, 1983). A shock to this variable is likely to directly affect the power of a wife and indirectly affect a wife's stove purchase decision. A test of validity of the instruments is conducted by using the Amemiya-Lee-Newey test of an over-identifying restriction.

Taking the patriarchal nature of the society into account, we use the term autocratic if the husband perceives that he makes the decision(s) on his own, moderate if he makes the decisions with his wife and non-autocratic if he lets his wife decide on her own. Conversely, a wife has high autonomy if she can make the decision on her own, moderate autonomy if she makes the decision with her husband and low autonomy if her husband makes the decision.

Our measure of autonomy (or autocracy) is a continuous variable based on the response of husbands and wives to survey questions about decisions regarding the wife's expenditure on her material needs (clothes, shoes, etc.) and household expenditures on household durable goods. For each of these two decision categories, we assign a value equal to 3 when each spouse thinks he/she has the power to decide, 2 when he/she thinks both make the decision and 1 when he/she thinks his wife/her husband makes the decision. These two decisions are important in this particular context for two reasons: the stove is generally a durable household item and husbands and wives may treat this stove as one of the wives'own material needs, such as clothes, for which the benefit is usually perceived to be largely for wives.

To check the robustness of the estimates of the above measures, an index of overall power is also constructed using these two questions and seven other decision categories. The additional decision categories asked about in the survey include: husband's expenditure on his material needs (clothes, shoes, etc.); expenditure on children's material needs (clothes, shoes, etc.); transfers made to husband's parents or relatives; transfers made to wife's parents or relatives; husband's labor force participation; wife's labor force participation; husband's visits to parents or friends; and wife's visits to parents or friends.

In the BDM experiment, we ask subjects to bid for the stove using the money they earned from the experiment. Because the BDM design is incentive compatible, subjects are expected to reveal their true preferences by stating their maximum WTP for the improved cookstove. However, their WTP may be bounded by the amount of money the subjects get from the experiment. In the data, the maximum that subjects state is 150, implying their boundedness. Therefore, following Wooldridge (2010, 785-790), we set the following censored model for WTP:

$$WTP_i^* = X_i\beta + \epsilon_i \quad (11)$$

Where ϵ_i is the error term, X_i is a vector of regressors, β is a vector of parameters and WTP_i^* is latent willingness to pay that is observed for values less than the upper bound set by the experiment design ($\tau = 150$) and censored otherwise. The observed WTP is defined by the following measurement equations;

$$WTP_i = \begin{cases} \tau \quad if\, WTP_i^* \geq \tau \\ WTP_i^* \quad if\, WTP_i^* < \tau \end{cases} \quad (12)$$

Assuming WTP_i is normally distributed with mean $X_i\beta$ and variance σ^2, we can use maximum likelihood estimation method using the following log likelihood function for censored normal regression model;

$$lnL_i = 1[WTP_i]ln[\frac{1}{\sigma}\Phi[\frac{(WTP_i - X_i\beta)}{\sigma}]] + 1[WTP_i = \tau]ln[1 - \Phi[\frac{(WTP_i - X_i\beta)}{\sigma}]] \quad (13)$$

One can use the STATA command Tobit with $ul(150)$ option to estimate the correlates of WTP. Because our interest is to estimate the causal relationship between intra-household bargaining power and subjects'WTP, we use the IV-Tobit method, using birth order and death shock of male siblings as instruments for the survey-based measure of power

In what follows, by making our explanatory variables of interest explicit in the latent WTP models, we provide descriptions of the variables of interest and discuss the expected signs of the parameters of these variables in relation to the hypotheses of the study. Equations (14), (15) and (16), displayed below, represent the latent WTP equations for the wives subsample, husbands subsample and pooled subsample (which includes individual husbands, individual wives and joint couples subsamples), respectively. In equation (14),WTP_{iw}^* denotes the wife's latent WTP, which includes their WTP from joint decisions; *Autonomy* is the survey-based measure of a wife's decision-making autonomy (power), taking a value 3 when she thinks she has the power to decide, 2 when she thinks both (husband and wife) make decisions and 1 when she thinks her husband makes decisions; IJD is a dummy regressor from the experiment, taking a value of 1 if a wife makes the stove purchase decision individually and 0 if the decision is made jointly; X_{iw} is a vector of other characteristics specific to each wife (such as her education), household level socio-economic characteristics (such as wealth), and location dummies; and ϵ_{iw} is the error term in the wife's equation.

$$WTP_{iw}^* = \beta_{0w} + \beta_{1w} Autonomy_{iw} + \beta_{2w} IJD_{iw} + X_{iw}\beta_{kw} + \epsilon_{iw} \tag{14}$$

Where the subscript w refers to the wives subsample, $i = 1, 2, 3..., n$ is observation for n number of wives in the sample and $k = 0, 1, 2, ..., k$ is a subscript for the k unknown parameters(β_{kw}) in the model. β_{1w} measures the effect of the wife's autonomy (power) on the willingness to pay; it is expected to be positive because wives are generally expected to have a high preference for improved stoves and this high preference is expected to be revealed when the wife has the autonomy (power) to make decisions based on her preference. β_{2w} measures the difference in the WTP between those wives who decide alone and those who decide together with their husband in the experiment. In a patriarchal society where men are dominant in decision-making, WTP in the joint (household level) decision may represent a husband's preference. For the society we are studying, we expect joint (household level) decisions to reflect the husband's preference. Considering this,β_{2w} may indicate the difference in the preference between husband and wife. This is based on the expectation that, controlling for the difference in the decision-making power among women, the wives'WTP in individual decision represent their true (individual) preference. Hence we expect β_{2w} to be positive and significant.

In equation (15),WTP_{ih}^* is the husband's latent willingness to pay, which includes his WTP from joint decisions; *Autocracy* is the survey-based measure of husband's autocracy (power) in decisions taking a value 3 when he thinks he makes decisions alone, 2 when he thinks both (husband and wife) make decisions and 1 when he thinks he let his wife decide; X_{ih} is a vector of other characteristics specific to the husband, such as his education, household level socio-economic characteristics such as wealth, and location dummies; and ϵ_{ih} is the error term in the husbands equation.

$$WTP^*_{ih} = \beta_{0h} + \beta_{1h} Autocracy_{ih} + \beta_{2h} IJD_{ih} + X_{ih}\beta_{kh} + \epsilon_{ih} \tag{15}$$

Where the subscript h refers to the husbands subsample, $i = 1, 2, 3..., n$ is observation for n number of husbands in the sample and $k = 0, 1, 2, ..., k$ is a subscript for the k unknown parameters(β_{kh}) in the model. β_{1h} measures the effect of the husband's power on WTP; it is expected to be negative because husbands are generally expected to have a low preference for improved stoves and this low preference is expected to be revealed when the husband is autocratic. As explained above, the estimate of the variable IJD (β_{2h}) measures the difference in the WTP between those husbands who make the stove decision alone and those who decide together with their wives. In this case, we expect insignificant differences between husbands'individual and joint WTP, on the expectation that joint (household level) decisions reflect the husbands'preference.

In equation 16, WTP^*_i is pooled latent willingness to pay of the husbands subsample and wives subsample, which includes their individual and joint WTP; *gender* is also a dummy variable taking a value of 1 for husbands and 0 for wives; *power* is variable measuring husbands'(wives') autocracy (autonomy) in decisions, on the scale of 1 to 3 discussed above; and ϵ_i is the error term in the pooled equation.

$$WTP^*_i = \beta_0 + \beta_1 gender_i + \beta_2 power_i + \beta_3 IJD_i + \beta_4 (power_i * gedner_i) + \beta_5 (IJD_i * gender_i) + X_i\beta_k + \epsilon_i \tag{16}$$

Where the subscript $i = 1, 2, 3..., n$ is observation for n number of husbands and wives in the sample and $k = 0, 1, 2, ..., k$ is a subscript for the k unknown parameters(β_k). β_1 measures the direct effect of the variable gender and it is expected to be negative. Because the wives'WTP is expected to vary positively with their decision-making power and husband's WTP is expected to vary negatively with their decision-making power, the power variable is interacted with gender to identify this differential effect of decision-making power across gender. We expect β_4 to be negative. Likewise, the IJD variable is interacted with gender to identify the differential effect of IJD across gender. The sum of the direct and indirect effects of the variable gender ($\beta_1 + \beta_4 power_i + \beta_5 IJD_i$) measures the marginal effect of the gender difference in preference. Further, given our expectation about β_{2w} , we expect β_{2w} and the marginal effect of gender in equation 16 (i.e,$\beta_1 + \beta_4 power_i + \beta_5 IJD_i$) to have opposite signs but relatively comparable magnitudes in absolute terms.

Using the follow-up data, we also estimate the effect of wives'autonomy on the use of the clean and energy efficient stoves where the stove use is measured by the length of time (number of months) the stove has been used by the wife since the household got the stove. Because the length of time the stove has been in use is a continuous dependent variable, a linear instrumental variable (IV) regression is used to estimate the effect of women's bargaining power on stove use. In this case, the samples from both BDM and free distribution villages are used because bargaining power and stove use information are surveyed in both villages. We expect insignificant difference in the use of the stove among wives with different levels of bargaining power. This is because cooking is the sole responsibility of wives and, controlling for other factors, all wives have equal incentives to use it, regardless of their power in the house.

5 Descriptive statistics

Descriptive statistics from survey

Tables 1 and 2 in Appendix B provide summary statistics of individual and household level characteristics obtained from the baseline survey conducted in the BDM and free distribution villages,respectively. Starting with the BDM villages, as can be seen from Table 1, husbands on average are 4.5 years older and have more political participation (58%) and off-farm work (60%), as opposed to 29% and 23% of wives participating in political activities and off-farm work, respectively. On the other hand, 81% of wives participate in fuelwood collection from communal forests, while only 16% percent of husbands participate in fuelwood collection. Wives spend on average 30 hours a month on fuelwood collection, as opposed to husbands'0.88 hours. The differences in age, political involvement, off-farm work, participation in fuelwood collection and number of hours spent in fuelwood collection are statistically significant based on the simple mean difference test statistics. However, there is no significant difference in education, numbers of male and female siblings who have died, number of living male and female siblings, and birth order.

On average, households in the BDM villages have 3.0 timad (0.76 hectare) of land, 37 thousand Ethiopian Birr or ETB ($1,963) of wealth in assets, and a household size of 5.7 people. Households in these villages, on average, spend 0.45 hours to collect a kilogram of fuelwood, spend 46.96 hours a month for fuelwood collection from communal forest land and collect 231 kilograms of fuelwood from this forest land. Such dependency on fuelwood from these communal forest lands can accelerate degradation of these forests. From Table 1, we can see that 52% of households do not have a separate kitchen for cooking and most of them do not have windows in the place where they cook and live. This means a large proportion of households in these villages, in particular household members who are responsible for cooking, may be subject to the health impacts of indoor air pollution. As can be seen from Table 2, households in the free distribution villages have similar characteristics to households in BDM villages with respect to age, education, political participation, off-farm work, participation in fuelwood collection, hours spent in fuelwood collection, numbers of male and female siblings who have died, number of living male and female siblings, birth order of the couples, household size, land size, wealth, etc.

"Tables 1 and 2 about here"

Furthermore, as can be seen from Table 3, in the BDM villages, there is no significant difference in the above variables and other explanatory variables between subjects who participate in individual and joint stove purchase decisions. This result supports the random selection of subjects into individual and joint purchase decisions.

"Table 3 about here"

Tables 4 shows the proportion of husbands and wives who are perceived to have high, equal (moderate) and low power to make decisions regarding purchase of wives material needs, purchases of household durable items and other household decisions.

"Table 4 about here"

From Table 4, we can see that 61% and 40% of wives perceived themselves as having a low level of autonomy to make decisions regarding purchases of durable household items and purchases of their own material needs, respectively. On the other hand, around 51% and 47% of husbands in the study area consistently perceived their dominance (autocracy) in these two purchase decisions. These decision-making results and the summary statistics displayed in Table 4 imply that women in the study area lack autonomy in decision-making and support the belief that the man is usually the default head of the household who controls the householdrq's cash accounts. Overall, these gender-specific summary statistics are similar to the general experience of gender imbalance in developing countries, where women work more at home and less for wage income, have low political participation, and lack autonomy regarding major household decisions.

In addition to the decision-making questions, in the baseline survey, following Mobarak et al.(2012), husbands and wives were asked separately to make a hypothetical choice between receiving a good (service) and getting a fixed amount of cash instead. The goods (services) supposed to be provided are fuel-saving improved stoves (50% efficiency), smoke reducing improved stoves (reducing smoke by half or more), improved seed (that raises productivity by 25%) and three months of free quality health service by a medical doctor. We asked choice questions for each item at each of the following cash offers: ETB 50, ETB 150, ETB 250 and ETB 500. For example, we asked "would you like to get an improved stove that saves fuel by half or ETB 50?" These questions help us to understand husbands'and wives'relative preferences for technologies along the lines of gender-based division of labor (i.e., improved seed versus improved stoves) and their preferences for improved stoves compared to other development interventions such as health care. Figure 1 in Appendix A portrays the proportions of husbands and wives who wanted to receive the good/service rather than the cash offers.

"Figure 1 about here"

From this figure, we can see that husbands'and wives'demand for quality health service is price insensitive, while their demand for improved stoves and improved seed is price sensitive. Along the lines of gender-based divisions of labor, husbands show relatively high preference for improved seed but low preference for all improved stove types. On the contrary, wives'preference for improved seed is almost as high as their preference for smoke reducing stoves. Wives have relatively higher preference for fuel-saving stoves than for smoke reducing stoves. Overall, from this we can see preference for technologies following the gender-based division of labor, and we also see that improved stoves are preferred less in comparison to other development interventions such as health care. Moreover, both husbands and wives prioritize the fuel-saving attribute of the stove more than the smoke-reducing attribute of stoves. These systematic differences in the preferences of each spouse for each item at each cash offer indicate their understanding of the questions. Furthermore, such systematic difference in preference for each of the above hypothetical goods/services by each spouse may also indicate that spouses are not acutely short of cash, implying that subjects can evaluate the pros and cons of a stove purchase experiment that involves cash earning.

Results from the BDM Stove Purchase Experiment

Results from the experiment are displayed in Tables 5-12 of Appendix B. Table 5 is constructed to show gender differences in preferences and the differences in WTP between the experimental decision types (individual vs. joint decisions), while Tables 6 -11 are constructed to show the relationship between WTP (from both individual and joint decisions) and the survey-based decision-making autonomy (autocracy). In Table 12, we present the difference in WTP between individual income and household (joint) income.

From Table 5, we observe that wives who make the decision individually are generally willing to pay ETB 35.67 more than husbands, which is equivalent to around 60 percent more WTP by wives compared to husbands. This difference is statistically significant using the simple two sample mean comparison test. Moreover, wives who make the decision individually are willing to pay ETB 27.34 more than those who make the decision with their husbands; however, there is no significant difference between husbands who make the decision individually and jointly. This simple result may support the hypothesis that the low household demand for improved stoves in rural areas of developing countries is in part due to husbands'very low preference for improved stoves.

"Table 5 about here"

We reexamine this hypothesis by taking the intra-household power relationship into account, as this is likely to affect our elicitation of willingness to pay. As can be seen from Tables 6 and 8, based on the two sample mean comparison test, there is no strong significant difference in the individual and joint WTP of husbands at any level of power. On average, husbands who are autocratic and moderate regarding the purchases of household durable items and wives material needs are willing to pay around one-third of the full cost of the improved stove, while the non-autocratic husbands are willing to pay at least ETB 50 more than autocratic and moderate husbands. A similar result is obtained if we use the overall index of power (see Table 10).

"Tables 6, 8 and 10 about here"

Contrary to the observed relationship between husbands'WTP and intra-household power, wives who have high and moderate autonomy and make the stove decision individually are willing to pay more than two times the WTP of autocratic and moderate husbands who make the decision individually (Tables 7 and 9). Husbands who are autocratic and moderate have a higher influence on joint WTP and on wives'individual WTP than do egalitarian husbands. Wives with low autonomy have low WTP in the individual and joint decisions. However, we see a surprisingly weak influence of moderately autonomous wives in joint decisions. Consistent with our expectation, wives with high autonomy have a consistently high WTP in both individual and joint decisions.

We investigate these results further using the overall index of power. As shown in Table 11, the results based on overall power are not very different from the results based on power over durable goods and material needs. Therefore, in patriarchal societies, such as rural households in Ethiopia in particular and Africa in general, these results support the coincidence of the observed low household demand for improved stoves and very low husbands'preference for these stoves

"Tables 7,9 and 11 about here"

These preliminary results imply the significance of empowering women to improve adoption of modern cookstoves in Africa. Economic empowerment of women through employment and other income-generating activities is thought to be a catalyst for women's development. Such empowerment is expected to increase respect, status, self-confidence, and decision-making power in households, communities, and institutions (Hill, 2011). As a result, economic empowerment of women is one of the eight Millennium Development Goals (MDGs) and is also considered an instrument for other development goals, such as reduction of the mortality rate for children under age five (United Nations Development Programme [UNDP], 2006; Hill, 2011; Orfei, 2012). A dollar earned by a wife is believed to improve the welfare of the family more than a dollar earned by a husband (UNDP, 2006; Chakraborty and De, 2011; Orfei, 2012). With this motivation, we expect that economic empowerment of women will also enhance the demand for clean and fuel-saving technologies. Results displayed in Table 12 indicate that wives who are fully entitled to earnings (permitted to work individually and earn individually in the experiment)[17] are willing to pay more than those who are made to use household (joint) income from the experiment. Nonetheless, there is no significant difference in husbands'willingness to pay between individual and household (joint) earnings. Husbands do not seem to differentiate between these two income sources. This implies that, with more women participating in paid labor, the adoption of clean and energy efficient stove technologies will become more common.

"Table 12 about here"

Descriptive statistics: length of time the improved stoves are in use

We used the follow-up survey data to assess to what extent the stoves, both those purchased through the BDM experiment and those distributed freely, have been in use by households. Figure 3 shows the percentage of households and the number of months the stoves were in use by households who purchased the stoves through the BDM experiment. The stoves were delivered in October, 2013 and surveyed for use in January-February, 2015.

"Figure 3 about here"

From Figure 3, we can see that around 61% of the households have used the stove for at least 10 months, of which 15% started using it in the month of delivery. From this figure, we can also see that around 10% have used the stove for three months, of which 4.5% started to use it in the last month (i.e., they have used it for only one month). Likewise, in the villages with free distribution, from Figure 4 we can see that around 58% of households have used the stove for at least 10 months, of which 15.32% started using it in the month of delivery.

"Figure 4 about here"

Among the households that received free distribution of stoves, around 8% have used the stove for three months, of which around 1% started to use it in the last month. In both villages, we observe that a large proportion of households have used the stove for at least 10 months (i.e., they have not delayed in using it). This implies that women are free to, and choose to, use improved stoves if they have access to them.

[17] This is generally related to the patriarchal nature of households in rural Ethiopia (Africa), where the decision to work and use the earned income is perceived to be decided by the husband.

6 Econometric Results

Instruments validity and first stage regression results

As discussed in the previous sections, our measure of autonomy (power) may be subject to omitted variable bias due to measurement error and/or due to unobserved individual specific factors such as wives'/husbands'ability to persuade the other spouse. We assume that wives who have the ability to persuade their husbands are more likely to state higher willingness to pay and are also likely to have higher decision-making power. To address the effect of this and other unobserved factors, we used the birth order of spouses and the number of male siblings of the spouses who died post-marriage. In order for these instruments to be valid, they must be relevant and exogenous, i.e., the instruments must be correlated with the endogenous variables and uncorrelated with the dependent variable (WTP). We test the relevance of these variables through the individual and joint significance test of the coefficients in the first stage regression. We test the exogeneity of the instruments using the Amemiya-Lee-Newey over-identification test. This is a test of the null hypothesis that the excluded instrument or instruments are uncorrelated with the error term; a rejection casts doubt on the validity of the instruments. A statistical test result of these instruments is shown in Table 13 of Appendix B..

"Table 13 about here"

As shown in column 1 of Table 13, both birth order and deaths of male siblings of wives are individually and jointly significant at the 1% level of significance. This implies that an earlier birth order of the wife is associated with greater autonomy and that a larger number of male siblings who died after the wife's marriage is associated with lower autonomy of the wife. These results are consistent with the expected contextual effect of the instruments, discussed in the empirical strategy section, implying that these two instruments are relevant from both contextual and statistical viewpoints. Moreover, the Amemiya-Lee-Newey over-identification test results also support the statistical validity of the instruments in the wives'sub-sample. Similar test results are also obtained for the husbands'sub-sample. In this table, we can also see the effect of other correlates, such as education and wives'outside options (off-farm employment), which have been used in the literature as measures of wives'bargaining power (Malhotra and Mather, 1997; Chakraborty and De, 2011). Both wives'education and their participation in off-farm income activities are positively and significantly correlated to our measures of wives'autonomy. Consistent with the patriarchal nature of rural households in the study area, wives'perceived power is significantly lower than that of husbands (see column 5 of Table 13). In the husbands'sub-sample, education is negatively correlated with perceived power, implying that husbands'education is likely to be an instrument to transform a patriarchal society into an egalitarian society.

Ivtobit Results: Willingness to pay, Autonomy (autocracy) and other Correlates

Estimates of the standard Tobit model and IV-Tobit model for the sub-samples of wives,husbands and the pooled sample (which includes individual husbands, individual wives and joint couples subsamples) are presented in Tables 14-15 of Appendix B. Tables 14 and 15, respectively, are based on wives'(husbands') autonomy (autocracy) in purchase decisions of durable items and wives material needs. Comparing the standard Tobit and IV-Tobit estimates of the autonomy (autocracy) variable in the wives'(husbands') sub-samples of Table 14 and 15, we observe that IV-Tobit estimates of autonomy (autocracy) in buying household durable items is higher by 41% (27%, in absolute terms) than the estimates of the standard Tobit. Likewise, IV-Tobit estimates of the autonomy (autocracy) of buying wives'material needs is also higher by 22% (28%, in absolute terms). This implies that the instruments improve the estimates of wives'autonomy in the purchases of durable items and their material needs by 41% and 22%, respectively, and improve the estimate of husbands'autocracy by around 27%.

"Tables 14 and 15 about here"

The estimates in column 7 of Tables 14 and 15 suggest that wives'autonomy with respect to the two decision items (components) is positively and significantly related to their willingness to pay for the stove. Conversely, estimates of these variables in column 9 suggest that husbands autocracy is negatively and significantly related to their willingness to pay. This supports the hypothesis that wives'autonomy is related to higher willingness to pay and husbands'autocracy is related to lower willingness to pay. Because the estimated coefficients of a top-coded censored regression model can be interpreted as if they were OLS coefficients (Wooldridge, 2010), all estimated coefficients of variables, except those that have interactions, are also marginal effect estimates. The marginal effects of all the variables for the IV pooled sample are also provided in Tables 14 and 15. These estimates suggest that wives who have higher autonomy to buy durable items or their own material needs are willing to pay ETB 40 more than wives with lower autonomy, whereas husbands who are autocratic in the decisions to buy durable items or wives'material needs are willing to pay at least ETB 32 less than the non-autocratic husbands. We get similar results if we use an overall index of power.[18]

In addition to the above survey-based measures of autonomy (autocracy) in decisions, we use an experimental measure of autonomy in the stove purchase decisions. The autonomy in decision-making during the experiment is proxied by individual versus joint stove purchase decisions. The variable individual (IJD) takes a value of 1 if the decision is individual and 0 otherwise. In the wives'sub-sample (column 7 of Tables 14 and 15), the estimate of this variable is positive and significant, implying that wives'individual decisions (autonomy) are related to higher WTP. As shown in Tables 14 and 15, at the margin, a wife deciding individually is correlated with almost ETB 21 higher WTP than a wife deciding with her husband. However, there is no significant difference between husbands deciding individually and jointly, implying that husbands'have high influence over household decisions.

One of the objectives of this study is to see the degree of difference in preference between husbands and wives, controlling for intra-household power differences, education, age, etc. We estimate this difference in preference by pooling the two sub-samples. The estimate of the variable gender, taking a value of 1 for a husband and 0 otherwise, captures the gender difference in preference. The estimate of this variable is negative and statistically significant, implying the expected lower willingness to pay of husbands. Marginally (in both Table 14 and 15), wives are willing to pay around ETB 28 more than are husbands, which is almost equivalent to the difference between the individual and joint WTP of wives. Further, as can be seen from the IV estimate of the pooled sample (in both Tables 14 and 15), the coefficient of the interaction of the variable gender with decision-making power is negative and statistically significant. This means an autocratic husband is willing to pay around ETB 70 less than an autonomous wife. Overall, this gender difference in preference results and effects of the difference in intra-household power relations implies the coincidence of the observed low household demand for improved stoves and the very low preference of

[18]To reduce the number of tables presented in this study, a regression result based on overall index of power is not provided. The result is available up on request.

husbands for this stove. Therefore, improved stove programs will not be successful if the intra-household power relationship and the preference differences of husbands and wives for this item are not considered, a result consistent with the findings of Miller and Mobarak (2013).

In our experiment, we try to proxy the effect of women's economic empowerment on the decision to buy the improved stove by making wives partially (joint earning) and fully (individual earning) entitled to earned income. In the regressions, the variable individual earning takes a value of 1 if the subject is using individual earning and 0 for joint earning. The coefficient of this variable is positive and significant for the wives'sub-sample but insignificant for the husbands'sub-sample. This implies that husbands do not treat these two income sources differently, while wives treat them differently. At the margin, wives who use individually earned income are willing to pay ETB 12 more than wives who use jointly earned income. This indicates the importance of creating opportunities for wives to participate in the paid labor market.

From Tables 14 and 15, we can see that husbands and wives who have a higher level of education are willing to pay more. This is consistent with the previous findings of the literature. El Tayeb and Mukhtar (2003) and Alem et al. (2014) find that the education of the housewife and other female members is more important for adoption of improved stoves than the education of male household members. The significance of husbands'education in this study may also be taken as an additional finding supporting the existing literature. Moreover, off-farm participation and having more children is also positively and significantly related to higher willingness to pay of both husbands and wives. The significance of off-farm participation is consistent with the time saving nature of the improved stove technology.

The significance of number of children in the wives sub-sample may imply wives'desire to reduce the inconvenience of collecting fuel while taking care of children, which are joint activities in the study area. Mekonnen (1999) also finds a negative correlation between number of children and women's collection of fuelwood from communal lands. The effect of the number of children in the husbands'sub-sample is surprising because fuel collection and child care are not their main responsibility. This positive and significant effect of number of children for husbands may be interpreted as husbands'desire to reduce the effect of indoor air pollution on children; in the experiment, we explained to subjects that the stove can reduce smoke by half. We can also see that wives and husbands from wealthy households are willing to pay more. In the pooled sample, we can see a negative and significant effect of the number of young and adult female members on WTP. These variables are also negative but insignificant in both the husbands'and wives'sub-sample. These results generally imply that female members of the household are the main supply of labor for fuel collection; the more of these "hands"a household has, the less it would need to adopt fuel-saving technology.

IV-Linear regression results: length of time the mproved stoves are in use, wives'autonomy and other correlates

Table 16 in Appendix B reports the linear IV regression of the number of months that wives used the improved stove in the BDM and free distribution villages. To reduce the number of tables in the paper, we have not provided OLS estimate of stove use. We find significant difference in the point estimate of the bargaining power variable between OLS and IV regression.[19] As stated in the previous paragraphs, this difference may be attributed to the endogeneity of the bargaining power variable and the improvement in the IV estimate using the aforementioned instruments.

As shown in table 16, the estimate of the bargaining power variable is statistically insignificant in both the BDM and free distribution villages, i.e., there is no significant difference among wives who have high, moderate and low power in the purchase of their material needs. A result, not reported here, also shows insignificant difference in stove use among wives who have high, moderate and low power in the purchase of household durable items. This result is also robust if the overall index of power is used. The insignificance of the bargaining estimate in all the villages and using all measures of power supports the hypothesis that bargaining power does not matter for the use of the improved stove once the household has made the decision to buy the stove. From Table 16, we can also see that stove use is positively and significantly correlated with the wife's education level and number of children in the house. The significance of education may imply that education has the power to speed up the use of these clean and energy efficient technologies. Further, the significance of number of children may imply a wife's desire to reduce the effect of indoor air pollution on children's health. It may also mean that wives with a large number of children start using the stove earlier to reduce the need to collect fuel in order to provide the frequent number of meals demanded by children.

[19]The OLS results can be provided upon request

7 Conclusion and policy implication

One of the sustainability challenges developing countries face is the transition from traditional stoves to improved biomass stoves. Inefficient traditional stoves consume a large quantity of fuel, which demands more cooking and fuel collection time for households in developing countries. This imposes a heavy work burden, specifically on females and children, who are traditionally responsible for these tasks. Furthermore, the high amount of smoke emitted from such traditional stoves results in indoor air pollution, which imposes serious health hazards on household members, especially women and children. Several efforts have been made to promote cleaner technologies in Ethiopia and other developing countries, but the adoption and use of these improved stoves is disappointingly low.

We conducted a real stove purchase experiment in six villages of southern Tigrai, Ethiopia, to study the role of gender differences in preference and wives (husbands) autonomy (autocracy) in explaining the observed low household level demand for improved stoves in Ethiopia. The Becker-DeGroot-Marschak (BDM) experiment method was used to reveal subjects preference (by stating the maximum willingness to pay) for a fuel-saving stove. The BDM design is incentive compatible and hence makes subjects reveal their true preference for the item. Moreover, survey and experimental measures of autonomy (power) are used to uncover the effect of autonomy on the demand for the improved stove. A follow-up survey was also conducted 15 months after the experiment to investigate whether there is a difference in the use of the clean and energy efficient stoves among wives with different levels of power.

We used both survey and experiment methods to study the effect of wives (husbands) autonomy (autocracy) on the demand for improved stoves. The survey based measure of autonomy includes husband and wives decision making power on the purchases of household durable items and wives material need such as clothes and shoes. These two decisions are important in this particular context, on one hand, because the stove is generally a durable household item and on the other hand husbands and wives may treat this stove as one of the wives own material need such as cloth because the benefit of it is largely perceived to be for wives. The experimental measure of autonomy (autocracy) is defined by using individual and joint decisions of representative husband, wife and joint couples.

The results indicate that wives generally have higher demand for the improved stove than do husbands. We find a statistically significant difference between individual and joint decisions of wives, while the difference is insignificant for husbands. This result is strengthened by the positive (negative) and statistically significant effect of wives'(husbands') autonomy (autocracy) in decisions regarding the purchases of household durable items and wives material needs. The fact that rural households in the study area and in Ethiopia generally are patriarchal implies that the result explains the coincidence of low observed household demand for stoves in the rural markets and experimental husbands'very low preference for improved stoves. Given the husbands'low demand, the external benefits of the new stoves (reducing demands on forests and greenhouse gas emissions) and wives low power, a subsidy of 50%-75% [20] may be needed to increase uptake of the stove. Furthermore, wives who are educated and have their own income source have higher demand for the improved stove. This implies that education for girls and opportunities for women to earn income can promote stove adoption. Unlike previous findings, husbands'education is also found to be strongly correlated with higher WTP.

Our follow-up survey shows that a large proportion of households (around 60%) used the stove for at least 10 months after the baseline survey and experiment. In the study area, less than 5% of the households have delayed the installation and used the purchased or acquired improved stove. The regression results also indicate insignificant difference in the length of time of the stove was in use among wives with different levels of power. These descriptive statistics and regression results imply that almost all women have equal incentives to use the improved stove and most are able to use it if they have access to it. Further, we find that educated women started to use the stove earlier than did uneducated women, which may imply that education has the power to speed up the use of these clean and energy efficient technologies.

This paper, however, may have the following limitations. First, subjects who participated in the BDM experiment carried out manual labor to earn income that enabled them to buy the improved stove. Doing these two activities at the same time may create some

[20]This is based on the predicted WTP. We calculated around a 50% subsidy at the average bargaining power and around a 70-75% subsidy if we take wives as having low bargaining power and husbands as having high bargaining power. In both predictions, we take a value of 1 for the individual decision (IJD) and individual earning variables. For all other socio-economic regressors in the models, we take their mean values.

fatigue and may have had some effect on the results. Yet, conducting an experiment with real labor income has the advantage of showing to what extent households in the study area can commit to a purchase decision from income obtained in exchange of labor. This is important because almost all households in the study area depend on earned income. If the study was conducted with windfall money, on the notion of "easy come - easy go"and the theory of mental accounting of money, we might find a different result. Second, because our sample size is small, it may be difficult to generalize the result we obtained to other locations. However, the finding could be of potential importance in other places where the man is considered the default household head who controls the household's cash account. Therefore, a direction for future research would be to conduct similar studies with more a comprehensive experimental design that takes into account both windfall and earned income and uses a larger sample size.

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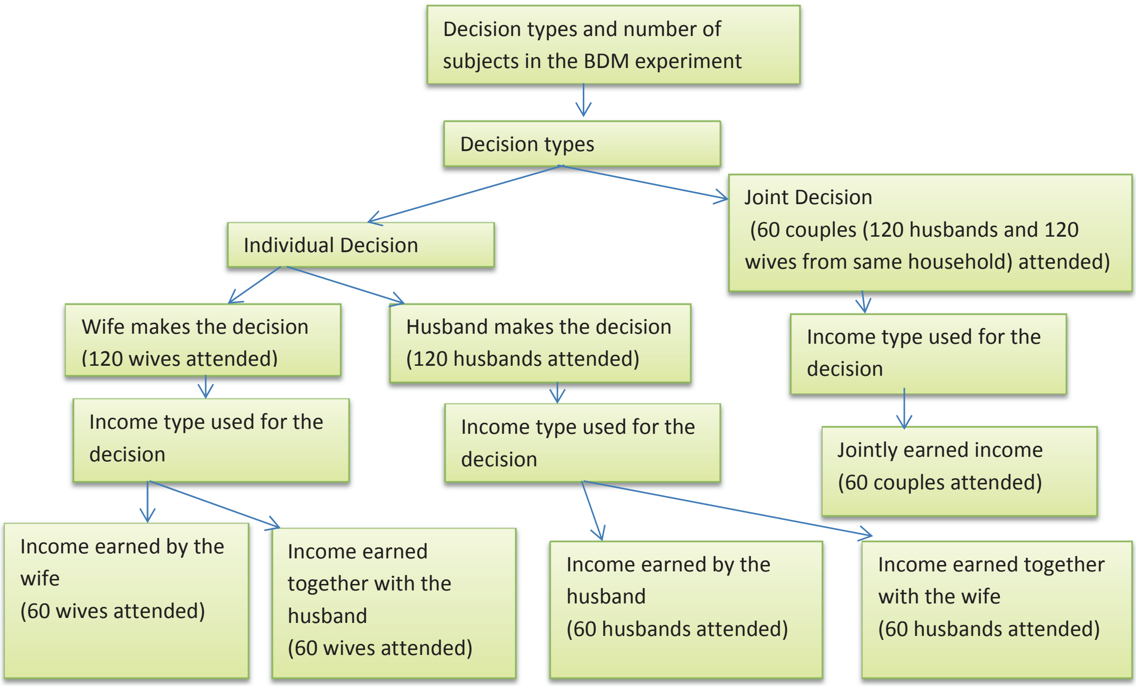
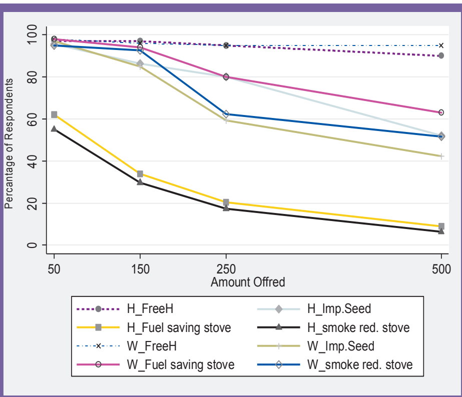
Appendix A: List of Figures

Fig 1: Group types, income types and number of subjects who attended the BDM Experiment.





Where:
H_FreeH=husbands' preference for 3 months of free health service by medical doctor to the amount offered
H_Imp. seed=husbands' preference for improved seed that increases productivity by 25% to the amount offered
H_Fuel-saving stove==husbands' preference for fuel-saving stove (50% saving) to the amount offered
H_smoke red. stove==husbands preference for smoke reducing stove (50% and above) to the amount offered
W_FreeH=wives' preference for 3 months free health service by medical doctorto the amount offered
W_Imp. seed =wives' preference for improved seed that increases productivity by 25% to the amount offered
W_Fuel-saving stove==wives' preference for fuel saving stove (50% saving) to the amount offered
W_smoke red. stove==wives' preference for smoke reducing stove (50% and above) to the amount

Fig 2: comparison of husband and wife preference for clean and fuel-saving stove, improved seed, and quality health service

Note: each curve is drawn from the response of each spouse to the question "would you like to get the good/service or ETB 50? 1. the good/service 2. Cash." We asked them again to choose between the good/service and ETB 150. We repeated this question for ETB 250 and ETB 500. These questions are also repeated for four goods/services which are supposed to be provided. These are 3 months free health service by a medical doctor, improved seed, fuel-saving stove (saving by half) and smoke reducing stove (by half or more).

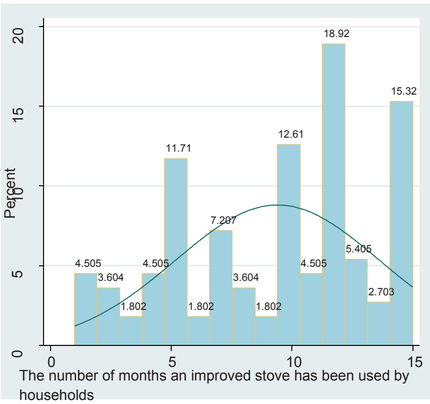


Fig 3: the percent of households who use the stove in each month since the stoves were purchased by the households in the BDM villages.

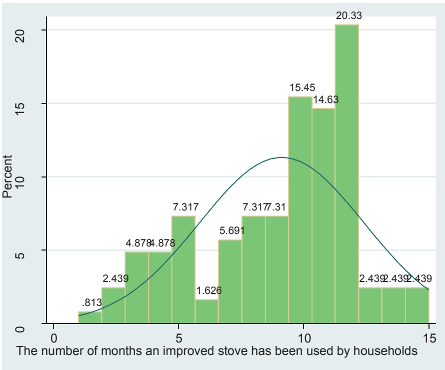


Fig 4: the percent of households who used the stove in each month since the stoves were given to the households in the free distribution villages.

Appendix B: List of Tables

Table 1: Descriptive statistics of individual and household characteristics for the BDM villages

Individual Characteristics	**Husband**		**Wife**		**Mean Difference**	
	Mean	**Std. Dev.**	**Mean**	**Std. Dev.**	**Dif.**	**Std. Err.**
Age	49.02	13.32	44.49	12.77	4.53***	1.06
Education in years	1.23	2.2	1.08	1.62	0.16	0.15
Member of the ruling party	0.58	0.49	0.29	0.45	0.27***	0.02
Participation in fuelwood collection	0.16	0.37	0.81	0.39	0.65***	0.03
Spouses' monthly time spent in fuel collection (in hours)	0.88	1.24	30.54	26.4	29.65***	1.53
Participation in off-farm income activities	0.6	0.49	0.23	0.42	0.36***	0.03
Number of male siblings died	0.41	0.38	0.4	0.71	0.01	0.06
Number of female siblings died	0.31	0.63	0.3	0.6	0.01	0.05
Number of male siblings alive	1.95	1.38	1.61	1.56	0.34	0.24
Number of female siblings alive	1.75	1.43	2.07	1.21	0.36	0.29
Birth order	2.04	1.37	2.7	1.65	0.65	0.54
Number of husbands/wives interviewed in the baseline survey	300		300			
Number of husbands/wives participated in the individual stove purchase decision	120		120			
Number of husbands/wives participated in the joint stove purchase decision	60		60			
Number of husbands/wives in the individual stove purchase decision using individual income	60		60			
Number of husbands/wives in the individual stove purchase decision using joint income	60		60			
Total number of husbands/wives participated in the experiment	180		180			

Household level characteristics	**Mean**	**Std. Dev**
Hours spent collecting per Kg of fuelwood (shadow price)	0.45	0.43
Household monthly time spent in fuel collection (in hours)	46.94	41.51
Household monthly fuelwood collection (in kg)	231.4	183
Household livestock Ownership (in TLU)	5.01	4.16
Household wealth in 1000 ETB	37.73	38.65
Household land size (in Timad)	3.03	2.22
Number of trees the household owns	11.58	32.25
Number of adult males (age >15)[a]	0.64	0.99
Number of adult female (age>15)[a]	0.65	0.95
Number of male youth (age >=7 and <=15)	0.69	0.98
Number of female youth (age >=7 and <=15)	0.92	1.06
Number of children (age<7)	0.87	0.99
Household size	5.7	1.7
Number of windows in the house	0.52	0.72
Separate kitchen (1=yes, 0=no)	0.52	0.5
Number of observations	600	

a= excluding spouses, ***= 1% significance level and 1 USD=18.85 ETB at the time of survey

Table 2: Descriptive statistics of individual and household characteristics for the free distribution villages

Individual Characteristics	Husband Mean	Husband Std. Dev.	Wife Mean	Wife Std. Dev.	Mean Difference Dif.	Mean Difference Std. Err.
Age	49.78	14.89	45.56	12.35	4.21***	1.12
Education in years	1.67	2.37	1.61	2.21	0.05	0.19
Member of the ruling party	0.66	0.47	0.25	0.43	0.40***	0.03
Participation in fuelwood collection	0.155	0.36	0.83	0.37	0.68***	0.03
Spouses' monthly time spent in fuel collection (in hours)	0.90	2.25	32.00	26.55	31.09***	1.54
Participation in off-farm income activities	0.70	0.45	0.25	0.47	0.45***	0.03
Number of male siblings died	0.54	0.91	0.51	0.83	0.02	0.07
Number of female siblings died	0.34	0.64	0.36	.65	0.016	0.05
Number of male siblings alive	1.86	1.52	1.70	1.47	0.16	0.12
Number of female siblings alive	1.91	1.35	1.88	1.34	0.02	0.11
Birth order	2.05	1.36	2.71	1.65	0.66	0.51

Household level characteristics	Mean	Std. Dev
Hours spent collecting per Kg of fuelwood (shadow price)	0.45	0.42
Household monthly time spent in fuel collection (in hours)	48.16	42.17
Household monthly fuelwood collection (in kg)	230.03	186.22
Household livestock ownership (Tropical Livestock Units/TLU)	8.10	4.60
Household wealth in 1000 ETB	38.26	38.30
Household land size (in Timad)	3.71	2.76
Number of trees the household owns	11.79	31.89
Number of adult males (age >15)[a]	0. 61	0.94
Number of adult females (age>15)[a]	0.64	0.96
Number of male youth (age >=7 and <=15)	0.68	0.97
Number of female youth (age >=7 and <=15)	0.92	1.06
Number of children (age<7)	0.88	1.01
Household size	5.62	1.76
Number of windows in the house	0.69	.83
Separate kitchen (1=yes, 0=no)	0.52	0.51
Number of observations	592	

Table 3: Probit Results of participation in individual vs. joint stove purchase decision

	Wives sub-sample		Husbands sub-sample		Pooled sample	
Variables	COEF	SE	COEF	SE	COEF	SE
Birth order of the subjects (B)	-0.01	0.07	0.01	0.08	0.01	0.05
Number of male siblings died (M)	-0.11	0.15	0.18	0.13	0.03	0.09
Gender (G)					-0.02	0.26
Power in the purchase of wife's material needs	-0.30	0.39	0.19	0.34	0.11	0.23
Power in the purchase of durables	-0.16	0.36	0.15	0.32	-0.05	0.23
Age	-0.01	0.01	0.01	0.01	0.00	0.01
Proportion of spouses' time in the total household fuel collection time	-0.06	0.30	-2.12	2.43	-0.04	0.28
Number of livestock in TLU	-0.00	0.02	0.01	0.04	0.00	0.02
Education level (in years)	0.09	0.07	0.06	0.05	0.04	0.04
Participate in off-farm income activities	0.23	0.25	-0.32	0.25	-0.07	0.16
Number of adult males	0.16	0.11	0.01	0.14	0.10	0.08
Number of male youth	-0.04	0.13	0.05	0.12	0.03	0.08
Number of adult females	0.04	0.11	0.08	0.12	0.09	0.08
Number of female youth	-0.08	0.10	-0.06	0.10	-0.05	0.07
Number of children	0.15	0.14	0.13	0.13	0.07	0.09
Number of windows in the house	-0.15	0.16	-0.12	0.14	-0.08	0.10
Separate kitchen (1=yes, 0=no)	-0.36*	0.22	-0.11	0.21	-0.16	0.14
Household's wealth	0.00	0.00	0.00	0.00	0.00	0.00
Household's land size	-0.01	0.06	-0.03	0.06	-0.02	0.04
Number of trees	0.00	0.08	-0.04	0.08	-0.04	0.05
Member of the ruling party	0.09	0.26	0.14	0.21	0.11	0.16
Village dummies						
Menkere	0.05	0.39	-0.19	0.39	-0.00	0.26
Adidemshash	0.12	0.37	-0.10	0.37	0.04	0.25
Adielmela	0.08	0.39	-0.25	0.40	-0.03	0.27
Adiagam	0.15	0.36	-0.04	0.38	0.03	0.25
Gararsa	0.16	0.38	0.04	0.39	0.04	0.25
Constant	1.36**	0.69	-0.57	0.74	0.21	0.49
Observations	180		180		360	

***= 1% level of significance, **=5% level of significance and *=10% level of significance

Table 4: Individual's perception of overall decision-making autonomy (autocracy) on the purchase of durable items, wives' material needs and overall decisions

Perceived levels of wives' autonomy on the purchase of durables	Number (%) of wives	Perceived levels of husbands' autocracy on the purchase of durables	Number (%) of husbands
Low level of autonomy	183(61%)	High dominance (autocrat)	154 (51.33%)
Moderate level of autonomy	62(20.67%)	Moderate	78 (26%)
high level of autonomy	55(18.33%)	Low dominance (Non-autocrat)	68 (22.67%)
Perceived levels of wives' autonomy on the purchase of wives' material needs	**Number (%) of Wives**	**Perceived levels of husbands' autocracy on the purchase of wives' material needs**	**Number (%) of husbands**
Low level of autonomy	119(40%)	High dominance (autocrat)	141(47%)
Moderate level of autonomy	94(31%)	Moderate	88(29.33%)
High level of autonomy	87(29%)	Low dominance (non-autocrat)	71(23.67%)
Overall perceived levels of wives' autonomy	**Number(%) of Wives**	**Perceived levels of husbands' autocracy**	**Number(%) of husbands**
Low level of autonomy (average index <2)	185(61.67%)	High dominance(autocrat)(average index >2)	177(59%)
Moderate level of autonomy (average index =2)	33(11%)	Moderate(average index =2)	45(15%)
High level of autonomy (average index >2)	82(27%)	Low dominance(Non-autocrat)(average index<2)	78(26%)

Average index from nine decision components	mean	St.d	Min	max	Average index from nine decision components	mean	St.d	Min	max
Average	1.71	0.49	1	3		2.3	0.58	1	3

Table 5: Mean WTP of husbands and wives when deciding individually or jointly

	Wives		Husbands		Mean Difference	
Decision types	Mean	Std. Dev (Err.)	Mean	Std. Dev (Err.)	Mean	Sd.Err.
Individual decision	96.17	40.72	60.5	34.77	35.67***	4.8
Joint decision	68.83	43.66	68.33	43.66	0	0
Mean difference	27.34***	(6.6)	-8.33	(6.00)		

***= 1% level of significance, **=5% level of significance and *=10% level of significance. Numbers in brackets are standard errors of mean differences

Table 6: Husbands' WTP , experimental decision types and perceived level of autocracy on the purchase of durables

	Individual		Joint		Mean Difference	
Husbands' perceived levels of dominance	Mean	Sd. Dev(err.)	Mean	Sd. Dev(err.)	Diff.	Sd. Err
Non-autocrat	107.38	24.8	121.25	33.44	-13.86	9.56
Moderate	53.08	29.49	63.88	39.72	10.80	9.71
Autocrat	49.23	10.67	40.67	10.67	9.23*	5.46
Mean diff b/n non-autocrat& autocrat	58.15***	6.64	81.25***	7.03		
Mean diff b/n non-autocrat &moderate	54.29***	7.72	57.36***	12.68		
Mean diff b/n moderate& autocrat	3.85	5.89	23.88***	8.15		

***= 1% level of significance, **=5% level of significance and *=10% level of significance. Numbers in brackets are standard errors of mean differences

Table 7: Wives' WTP, experimental decision types and perceived level of autocracy on the purchase of durables

	Individual		Joint		Mean Difference	
Wives' perceived levels autonomy	Mean	Sd. Dev(Err.)	Mean	Sd. Dev(Err.)	Diff.	Sd. Err
Low level of autonomy	66.82	28.61	40.67	10.67	26.82***	5.78
Moderate level of autonomy	115.96	25.30	63.88	39.72	52.07***	9.79
High level of autonomy	139.19	17.08	121.25	33.44	17.94***	7.33
Mean diff b/n low & high autonomy	-72.36***	5.58	-81.25***	7.03		
Mean diff b/n low &moderate autonomy	-49.13***	6.46	-23.88***	8.15		
Mean diff b/n moderate& high autonomy	-23.23***	5.64	-57.36***	12.68		

***= a student t-test 1% level of significance , **=5% level of significance and *=10% level of significance

Table 8: Husbands WTP, Experimental decision types and perceived level of autocracy on the purchase of wife's material needs

	Individual		Joint		Mean Difference	
Husbands' perceived levels of dominance	Mean	Sd. Dev(err.)	Mean	Sd. Dev(err.)	Diff.	Sd. Err
Non-autocrat	106.67	23.73	122	34.47	-15.33	9.68
Moderate	56.97	32.38	66.31	40.02	-9.34	9.60
Autocrat	45.89	23.86	40	10.67	5.89	4.90
Mean diff b/n non-autocrat& autocrat	60.77***	6.09	82***	7.24		
Mean diff b/n non-autocrat &moderate	49.68***	7.95	55.68***	13.02		
Mean diff b/n moderate& autocrat	11.08*	5.65	26.32***	8.19		

Table 9: Wives' WTP, experimental decision types and perceived level of autonomy on the purchase of wives' material needs

	Individual		Joint		Mean Difference	
Wives' perceived levels Autonomy	Mean	Sd. Dev(Err.)	Mean	Sd. Dev(Err.)	Diff.	Sd. Err
Low level of autonomy	61.44	20.23	40	10.67	21.44***	4.21
Moderate level of autonomy	114	23	66.31	40.02	47.07***	9.55
high level of autonomy	141.42	15.5	122	34.47	19.42***	7.02
Mean diff b/n low & high autonomy	-79.99***	3.97	-82***	7.24		
Mean diff b/n low &moderate autonomy	-52.14***	5.13	-26.31***	8.19		
Mean diff b/n moderate& high autonomy	-27.39***	5.04	55.68***	13.02		

***= a student t-test 1% level of significance , **=5% level of significance and *=10% level of significance

Table 10: Husbands WTP, experimental decision types and index of overall perceived level of autocracy

	Individual		Joint		Mean Difference	
Husbands' perceived levels of dominance	Mean	Sd. Dev(err.)	Mean	Sd. Dev(err.)	Diff.	Sd. Err
Non-autocrat	105.34	22.35	125.52	32.18	-20.47**	7.9
Moderate	46.57	17.37	44	8.09	2.57	6.08
Autocrat	46.11	25.73	42.01	16.55	4.01	4.8
Mean diff b/n non-autocrat& autocrat	59.23***	(5.4)	83.42***	(6.3)		
Mean diff b/n non-autocrat &moderate	58.76***	(6.14)	81.53***	(10.43)		
Mean diff b/n moderate& autocrat	0.46	(6.29)	1.9	(3.8		

Where, ***= 1% level of significance, **=5% level of significance and *=10% level of significance and those in brackets are standard errors of mean differences

Table 11: Wives' WTP, experimental decision types and index of overall perceived level of autonomy

	Individual		Joint		Mean Difference	
Wives' perceived levels Autonomy	Mean	Sd. Dev(Err.)	Mean	Sd. Dev(Err.)	Diff.	Sd. Err
Low level of autonomy	73.38	32.28	42.09	11.31	31.29***	5.95
Moderate level of autonomy	120.93	24.23	44	8.09	76.93***	7.97
high level of autonomy	139.17	17.37	125.52	32.18	13.64*	7.07
Mean diff b/n low & high autonomy	-65.78***	6.24	-83.42***	6.3		
Mean diff b/n low &moderate autonomy	-47.55***	8.56	-1.9	3.8		
Mean diff b/n moderate& high autonomy	-18.22***	6.15	-81.53***	10.43		

***= a student t-test 1% level of significance , **=5% level of significance and *=10% level of significance

Table 12: Mean WTP of husbands and wives when deciding using individual or joint income

Income types	Wives		husbands		Mean Difference	
	Mean	Std. Dev (Err.)	Mean	Std. Dev (Err.)	Mean	Sd.Err.
Individual earning	100.41	38.38	59.25	35.61	41.17***	6.75
Joint earning	80.38	44.6	65.29	39.19	15.08***	5.42
Mean Difference	20.04***	6.7	-6.04	6.01		

***= 1% level of significance, **=5% level of significance and *=10% level of significance

Table: 13: First stage regressions

	Wives' sub- sample		Husbands' sub-sample		Pooled sample	
	Power		Power		Power	
Variables	COEF	SE	COEF	SE	COEF	SE
Birth order of the subjects(B)	-0.103***	0.032	-0.143***	0.034	-0.141***	0.026
Number of male sibling died(M)	-0.216***	0.07	-0.132**	0.058	-0.281***	0.049
Gender(G)					0.241*	0.14
Individual(1) or joint(0) decision(IJD)	-0.128	0.122	0.074	0.112	0.034	0.095
Individual earning(1) or Joint earning(0)	-0.158	0.126	0.015	0.113	-0.009	0.097
Age	0.002	0.004	0.001	0.004	0.003	0.003
Proportion of spouses' time in total household fuel collection time	0.018	0.139	-4.585***	1.047	0.076	0.15
Number of livestock in TLU	-0.012	0.011	-0.019	0.016	-0.013	0.01
Education level(in years)	0.092***	0.032	-0.031	0.022	0.002	0.021
Participate in off-farm income activities	0.308***	0.117	0.622***	0.104	0.442***	0.089
Number of adult males	0.043	0.051	-0.033	0.059	0.028	0.044
Number of male youth	-0.019	0.06	0.055	0.051	0.038	0.044
Number of adult females	-0.035	0.056	0.127**	0.051	0.009	0.043
Number of female youth	-0.072	0.049	0.094**	0.047	0.013	0.039
Number of children	0.169***	0.06	-0.125**	0.058	0.036	0.048
Number of windows in the house	-0.224***	0.076	0.028	0.066	-0.076	0.057
Separate kitchen(1=yes, 0=no)	-0.283***	0.103	0.038	0.093	-0.09	0.079
Household wealth	0.001	0.001	-0.001	0.001	0	0.001
Household land size	-0.007	0.026	-0.003	0.025	0.004	0.021
Number of trees	0.044	0.038	0.005	0.036	0.008	0.03
Village dummies	Yes		Yes		Yes	
constant	0.04	0.295	0.211	0.281	-0.091	0.256
Amemiya-Lee-Newey over-identification test	Chi.sq(1)	P-value	Chi.sq(1)	P-value	Chi.sq(1)	P-value
test result	0.065	0.8	2.28	0.13	1.34	0.25
Joint test of significance for birth order and male sibling died	F-vale	P-value	F-vale	P-value	F-vale	P-value
test result	9.21	0.00	11.37	0.00	31.85	0.00
R2	0.50		0.47		0.31	
Number of observations	180		180		360	

***= 1% level of significance, **=5% level of significance and *=10% level of significance

Table 14: Tobit and IV-Tobit results of WTP using subjects' perceived power in the purchase of durables

	Standard Tobit Results						Iv-Tobit Results							
	Wives-sub sample		husbands-sub sample		Pooled sample		Wives-sub sample		husbands-sub sample		Pooled sample		Marginal effect of pooled IV	
VARIABLES	COEF	SE	COEF	SE	COEF	SE	COEF	SE	COEF	SE	COEF	SE	COEF	SE
Power in the purchase of durables$^{\$\$}$	29.16***	2.57	-26.44***	2.83	30.59***	2.49	40.84***	8.75	-32.82***	8.21	41.02***	9.04	6.64	4.29
Gender (G) of the subject					-3.89	5.84					-5.27	6.09	-28.74***	5.72
Individual(1) or joint(0) decision(IJD)	20.86***	4.17	-1.7	4.57	20.79***	4.46	22.93***	4.7	-0.42	4.83	22.08***	4.69	9.78***	3.28
Individual earning(1) or Joint earning(0)(IJE)	11.06**	4.37	-2.8	4.52	10.89**	4.59	13.53***	4.99	-3.17	4.56	12.47**	4.88	5.00	3.29
P X Gender					-57.38***	3.64					-68.75***	10.17		
IJD X Gender					-23.63***	6.25					-24.62***	6.46		
IJE X Gender					-13.20**	6.32					-14.93**	6.64		
Age	0.29*	0.15	-0.05	0.16	0.12	0.11	0.27*	0.16	-0.05	0.16	0.11	0.11	0.11	0.11
Proportion of spouses' time in total household fuel collection time	3.85	4.81	91.30**	43.86	5.55	4.98	3.78	5.14	63.24	55.54	4.47	5.15	4.47	5.15
Number of livestock in TLU	0.07	0.37	-0.5	0.65	-0.44	0.32	-0.24	0.42	-0.6	0.67	-0.3	0.35	-0.3	0.35
Education level(in years)	3.91***	1.12	3.55***	0.91	4.12***	0.7	3.26**	1.37	3.32***	0.95	3.71***	0.79	3.71***	0.79
Participate in off farm income activities	14.15***	4.11	12.77***	4.45	15.46***	3.04	13.36***	5.08	16.32***	6.19	14.10***	3.31	14.10***	3.31
Number of adult males	-0.58	1.78	1.44	2.37	0.45	1.45	-0.07	1.96	1.4	2.39	0.18	1.5	0.18	1.5
Number of male youth	-1.57	2.02	1.78	2.06	-0.07	1.44	-0.74	2.19	2.19	2.13	0.3	1.51	0.3	1.51
Number of adult females	-3.47*	1.89	-0.03	2.07	-1.35	1.42	-2.33	2.08	0.79	2.3	-0.78	1.53	-0.78	1.53
Number of female youth	-1.76	1.69	-2.54	1.91	-2.21*	1.28	-0.95	1.91	-1.92	2.07	-1.69	1.38	-1.69	1.38
Number of children	9.13***	2.12	7.36***	2.34	8.25***	1.6	6.93***	2.58	6.54**	2.55	7.20***	1.85	7.20***	1.85
Number of windows in the house	0.05	2.65	0.48	2.66	-0.3	1.89	2.94	3.53	0.68	2.69	0.77	2.13	0.77	2.13
Separate kitchen(1=yes, 0=no)	0.04	3.6	5.67	3.79	4.19	2.64	5.41	4.57	6.14	3.85	5.51*	2.92	5.51*	2.92
Household wealth	0.08*	0.04	0.19***	0.05	0.14***	0.03	0.08*	0.05	0.19***	0.06	0.13***	0.04	0.13***	0.04
Household land size	0.08	0.92	-0.18	1.02	-0.15	0.68	-0.11	0.98	-0.17	1.02	-0.22	0.7	-0.22	0.7
Number of trees	-0.82	1.32	0.33	1.45	0.36	0.98	-0.68	1.48	0.35	1.46	0.16	1.02	0.16	1.02
Village dummies	Yes		Yes		Yes		Yes		Yes			Yes	Yes	
Constant	46.23***	9.83	47.79***	11.12	49.79***	8.61	49.25***	10.71	46.62***	11.27	52.75***	8.99		
Sigma	21.64***	1.28	24.10***	1.34	23.54***	1								
Observations	180		180		360		180		180		360		360	

***= 1%, **=5% and *=10% level of significances.

Table 15: Tobit and IV-Tobit results of WTP using subjects' perceived power in the purchase of wives' material needs

	Standard Tobit Results						Iv-Tobit Results							
	Wives-sub sample		husbands-sub sample		Pooled sample		Wives-sub sample		husbands-sub sample		Pooled sample		Marginal effect of pooled IV	
VARIABLES	COEF	SE	COEF	SE	COEF	SE	COEF	SE	COEF	SE	COEF	SE	COEF	SE
Power in the purchase of wives' material needs(P) $^{\$\$}$	33.12***	2.45	-28.24***	3.06	33.90***	2.43	40.25***	7.58	-36.06***	8.67	40.99***	8.16	5.89	3.81
Gender (G) of the subject					-4.94	5.61					-6.05	5.81	-29.20***	4.98
Individual(1) or joint(0) decision(IJD)	20.08***	3.81	-4.38	4.55	19.81***	4.27	21.02***	4.03	-3.67	4.67	20.35***	4.37	7.62**	3.06
Individual earning(1) or Joint earning(0)(IJE)	10.90***	4.02	-1.99	4.52	10.10**	4.42	12.09***	4.30	-2.17	4.60	10.79**	4.54	4.75	3.09
P X Gender					-62.30***	3.62					-70.20***	9.41		
IJD X Gender					-25.11***	5.98					-25.46***	6.07		
IJE X Gender					-11.30*	6.09					-12.06*	6.22		
Age	0.18	0.14	-0.05	0.16	0.06	0.11	0.15	0.15	-0.04	0.16	0.04	0.11	0.04	0.11
Proportion of spouses' time in total household fuel collection time	3.44	4.40	63.43	44.92	4.72	4.78	3.20	4.53	23.55	61.47	3.98	4.91	3.98	4.91
Number of livestock in TLU	-0.50	0.33	-0.34	0.65	-0.48	0.31	-0.39	0.36	-0.42	0.67	-0.41	0.33	-0.41	0.33
Education level(in years)	3.49***	1.04	3.56***	0.91	3.71***	0.67	2.83**	1.25	3.30***	0.96	3.38***	0.77	3.38***	0.77
Participate in off farm income activities	14.26***	3.81	15.23***	4.57	15.19***	2.94	11.67**	4.69	19.95***	6.74	14.10***	3.20	14.10***	3.20
Number of adult males	0.56	1.63	-0.24	2.38	-0.04	1.39	0.17	1.72	-0.76	2.48	-0.20	1.42	-0.20	1.42
Number of male youth	-0.80	1.85	1.65	2.06	0.32	1.38	-0.43	1.94	2.10	2.15	0.59	1.43	0.59	1.43
Number of adult females	-2.64	1.73	0.31	2.08	-1.04	1.37	-2.23	1.83	1.34	2.37	-0.64	1.45	-0.64	1.45
Number of female youth	-1.11	1.56	-2.14	1.93	-1.72	1.24	-0.55	1.70	-1.33	2.13	-1.35	1.32	-1.35	1.32
Number of children	7.45***	1.96	6.61***	2.36	7.14***	1.54	6.21***	2.37	5.46**	2.67	6.29***	1.82	6.29***	1.82
Number of windows in the house	0.96	2.44	0.80	2.67	0.36	1.81	2.75	3.08	1.13	2.73	1.12	2.01	1.12	2.01
Separate kitchen(1=yes, 0=no)	4.21	3.33	5.33	3.79	4.62*	2.54	6.48	4.12	5.80	3.88	5.56**	2.77	5.56**	2.77
Household wealth	0.11***	0.04	0.20***	0.05	0.15***	0.03	0.10**	0.04	0.20***	0.06	0.14***	0.03	0.14***	0.03
Household land size	0.55	0.85	-0.46	1.02	0.10	0.66	0.64	0.87	-0.54	1.04	0.14	0.67	0.14	0.67
Number of trees	0.14	1.21	0.66	1.45	0.60	0.95	-0.19	1.29	0.77	1.48	0.49	0.97	0.49	0.97
Village dummies	Yes		Yes		Yes		Yes		Yes					
Constant	51.15***	9.07	66.07***	8.33	55.30***	8.13	53.76***	9.68	51.00***	11.31	57.96***	8.73	57.96***	8.73
Sigma	19.83***	1.17	23.82***	0.97	22.59***	0.91								
Observations	180		180		360		180		180					

***= 1%, **=5% and *=10% level of significance.

Table 16: IV regression of the number of months wives use improved stoves in the sampled villages

	BDM Villages		Free distribution villages		All villages	
VARIABLES	Coef. (1)	R.SE (2)	Coef. (3)	R.SE (4)	Coef. (3)	R.SE (4)
Bargaining power of the wife in the purchase of her material needs	0.11	1.00	-0.35	0.26	-0.67	0.87
Age	0.00	0.03	-0.01	0.01	-0.01	0.01
Wife's time in total household fuel collection time	-1.00	0.80	2.39***	0.79	0.93*	0.53
Number of livestock in TLU	-0.01	0.06	-0.35***	0.06	-0.22***	0.04
Wife's education level(in years)	0.82***	0.19	0.24***	0.09	0.48***	0.10
Wife's participation in off-farm income activities	0.61	0.73	2.12***	0.33	2.20***	0.42
Number of adult males in the wife's household	0.42	0.31	1.49***	0.28	1.21***	0.21
Number of male youth in the wife's household	0.16	0.33	-0.07	0.18	0.04	0.21
Number of adult females in the wife's household	-0.17	0.33	0.42**	0.18	0.18	0.21
Number of female youth in the wife's household	-0.50	0.31	0.21	0.16	-0.06	0.19
Number of children in the wife's household	0.96***	0.35	0.47**	0.19	0.74***	0.22
Number of windows in the house	0.13	0.44	-0.76***	0.19	-0.75***	0.26
Separate kitchen(1=yes, 0=no)	-0.05	0.58	-0.05	0.35	-0.31	0.37
Household wealth	0.01*	0.01	-0.00	0.01	0.01	0.00
Household land size	-0.23	0.16	0.09	0.08	0.05	0.08
Number of trees	0.06	0.21	0.02	0.13	0.05	0.14
Village dummies						
Constant	3.38**	1.67	1.58	1.18	2.31**	1.15
Observations	300		296		596	
R-squared	0.21		0.66		0.31	

Where ***= 1%, **=5% and *=10% level of significance and R.SE is robust standard error

Appendix C

Experiment Script

Step 1: Base line survey Before we start the survey, the village cadres introduce the enumerators to the subjects to be interviewed. The cadres use general statements that we came from Mekelle University for a study in their village. Following the introduction by the cadres, the enumerators use the following introductory statement:

"Good morning/good afternoon. We are happy that the village cadre has passed on our message and that we find you at home. We are sent by Mekelle University for a study on the socio-economic conditions of households in Tigrai and you and your village are randomly selected to be part of the study. The study involves asking husbands and wives survey questions on their socio-economic conditions. We will ask question during two time periods: today and two weeks from today. Today we will ask survey questions at your place for a maximum of two hours. It is important that both husband and wife participate in today's survey. After completing today's interview, either husband or wife, or both, will be randomly selected to further participate for the next study period that involves participation in paid labor work (weeding) at the farm land of the farmers'training center for at most four hours and two more hours for a similar study. The next study period demands that the randomly selected husband/wife/both be at the farmers'training center at 7AM/9AM. Will you participate in today's survey?

(If yes, we start the survey)

(If no, we say thank you and ask if we can interview them any time before next period of the study.

If yes, we ask them for a suitable time for the interview)

After completing the survey, we make the random draw for the next period of the study and ask the selected husband/wife/both if they are willing to participate in the next period of the study.

(If yes, we tell them the time and date that they should arrive at the farmers'training center)

(If no, we ask why he/she/they is/are not willing to participate.)

Step 2: Experiment

Stage 1 of step 2: Weeding activities and earn income

Upon arrival at the place of the experiment (the farmers'training center), in cooperation with the administrators of the farmers'training center, we informed subjects who came without their partners that they would weed for four hours in the center's plots, while those who came with their partner would each weed for two hours and it was required that both partners work for these hours. After completing the weeding activity, we also told them that they would stay for two more hours for a study about cooking stoves. At the end of the study, joint spouses would be paid a total of 150 ETB and those who came without their partner would also be paid ETB 150 as compensation for all the time they spent in weeding and in the experiment. We also told them that it was not possible to choose only one of the two activities (either weeding or participating in the experiment). If they did not participate in the experiment, we did not allow them only to work in the weeding activity and earn money, and vice versa. No payment would be given if they did not participate in both activities.

Stage 1 of step 2: Weeding activities and earn income

After completing the weeding activity, we gathered all the subjects in one place and told them that they would stay with us for two more hours for a study about an improved cookstove. Before we started the actual study, we told the subjects that we would give them a demonstration of the attributes of the new cooking stove. In the demonstration, the experimenter explained the fuel saving, smoke reduction, time saving, life span and other attributes of the new cooking stove. The experimenter used the following statements.

"The stove that you all see here is called 'MIRT '. It is made of cement concrete and has an estimated life span of 15 years. It reduces fuel consumption by half. To make it clear, the traditional stove which you are using now consumes 10 wood sticks (shilen - a wood type common in the area) to bake 20 pieces of injera. You can bake the same number of injera using only 5 wood sticks with this new stove. Another important feature of this stove is that you can cook wot using the same fuel which you use to bake injera. This will save your time and energy. The stove will also reduce the smoke by half. Such reduction in smoke has the advantage of

reducing health problems associated with smoke." Subjects were also trained how to assemble and disassemble the new cookstove.

Stage 3 of step 2: Becker-DeGroot-Marschak (BDM) bidding experiment After the completion of the demonstration about the stove, we divided the subjects into five groups and placed them in different places that were far apart. For each group, an experimenter explained about the Becker-DeGroot-Marschak (BDM) bidding game which was used to make the subjects reveal their preference for the new, energy efficient stove. We used the following statements to explain the experiment.

"We explained to you earlier about the new attributes of the improved stove and its benefits. We are interested in knowing how much you are willing to pay for this new improved stove. You can use the 150 ETB you have earned to buy the improved stove. There is no obligation to buy the improved stove. We will ask you to tell us the maximum price you are willing to pay for the improved stove.

At the end, all groups will gather together and one subject amongst you will be randomly selected to choose a ball from a bucket containing different small balls representing each possible price. Inside each ball, we put a small slip of paper. Different prices are written on each slip (bucket, sample slip papers and balls were shown). If the price you tell me is greater than the price chosen randomly, you will have an improved stove and pay us the price chosen. You will keep the difference between the total money you earn and the price drawn. However, if the price you tell me is less than the price chosen, you will get your money but you will not have the stove. You might wonder why we ask you to give a bid for the stove instead of just asking you to pay a price. Well, this research tries to establish how valuable such improved stoves are to you. We would therefore ask you to think carefully about the most you would be willing to pay for the stove. Therefore we ask you to tell us exactly the maximum price you are willing to pay; no more, no less. If the price you tell us is greater than your actual willingness to pay, you will be forced to pay it if that price is chosen. If the price you tell us is lower than your actual willingness to pay, then if a lower price is drawn and you find this price cheap, you will not have the stove even if you want to have it. Once the price is drawn, you are not allowed to

change your price. The information you will give us will determine whether you will buy the improved stove or not.
We will give you color copies of currency notes representing currency, and we will give you envelopes where you can put your bid price. (Copies of currency notes adding up to 665 were given to each subject: 4 pieces of 100 ETB paper currency; 4 pieces of 50 ETB paper currency; 4 of pieces of 10 ETB paper currency; 4 of pieces of 5 ETB paper currency; and 5 of pieces of 1 ETB paper currency). You are not allowed to talk or see others'price and you should also hide your bids from being seen by others. Once you decide how much you want to pay for it, put the amount of paper currency notes that you would like to pay in the envelope and seal it. We will come to your seats to collect the envelope. You are also not allowed to talk to each other and ask questions in public. If you have questions, raise your hand and I will come and talk to you privately and quietly."

Before they started the actual biding for the improved stove, we did the practice using pencils (as described in "Experiment design and procedures"). The following statements are used for this session:
"We will give you tokens representing coins and an envelope to put your bids in. We will give you an extra ETB 5 to practice the experiment procedure in buying improved pencils. You are not obliged to buy the pencil. You can use the ETB 5 for whatever you want. Now we will ask you to tell us the maximum price you are willing to pay for this pencil. You will put tokens in the envelope and seal it. A subject amongst you will randomly choose a ball from the bucket containing different small balls (like the above balls) representing each possible price. If the randomly drawn price is less than the amount you want to pay, you will get the pencil and you will pay money equal to the chosen price. But if the price is greater than the amount you want to pay, we will keep the pencil and you keep your money. We will do this once with real money. Do you have questions"

After collecting each subject's bid price, we gathered all the subjects again in one place to choose a price randomly. The random prices were: 30, 45, 60, 75, 90,105, 120, 135 and 150.

Paper II

Disadoption, substitutability and complementarity of agricultural technologies: A Random Effects Multivariate Probit Analysis.*

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Abstract

In this paper, we analyze what drives farmers to disadopt green revolution technologies (inorganic fertilizer and improved seed) and whether the disadoption of green revolution technologies is related to adoption/non-adoption of other sustainable land management practices (such as farmyard manure and soil and water conservation practices). Random effects multivariate probit regression results based on rich plot level data suggest that black/brown soil type, flatter slope, shorter distance to homestead and extension centers, and access to water are negatively correlated with disadoption of green revolution agricultural technologies. Further, we find that the disadoption of green revolution technologies is related to the non-adoption of other sustainable land management practices. Our results strengthen previous findings of complementarity between green revolution technologies and sustainable land management practices by showing that the latter can reduce the likelihood of disadoption of green revolution inputs.

JEL Classification: Q01, Q12, Q16, Q18

Key Words: Adoption, disadoption, agriculture, technology, multivariate probit, Ethiopia

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1 Introduction

Increasing agricultural productivity through the adoption and continued use of green revolution technologies (improved seed and inorganic fertilizer) and other sustainable land management practices (such as soil and water conservation practices and farmyard manure) has long been seen as a key policy option to curb undernourishment in Africa. Despite numerous efforts to enhance the adoption and diffusion of such beneficial practices, their use in rural Africa is low and thus a significant proportion of the population in Africa is malnourished (O'Gorman, 2006; Teklewold et al., 2013). Several adoption studies have been conducted in Africa and other developing countries to identify the reasons for low adoption (e.g., Croppenstedt et al., 2003; Marenya and Barrett, 2007; Kassie et al., 2009; Alem et al., 2010; Wollni et al., 2010; Dercon and Christiaensen, 2011; Teklewold et al., 2013). This paper focuses on the disadoption of green revolution technologies and on the relationship between green revolution technologies and other sustainable land management practices in disadoption decisions. These are issues which have been given inadequate emphasis in the literature.

Existing studies on agricultural technology adoption in developing countries find the following factors as the most important in limiting the take-up of new agricultural technologies: risk and uncertainty, knowledge and education, profitability, input availability, credit constraints, tenure security, labor availability, biophysical factors, market incentives and social networks (Croppenstedt et al., 2003; Pattanayak et al., 2003; Bandiera and Rasul, 2005; Doss, 2006; Marenya and Barrett, 2007; Kassie et al., 2009; Alem et al., 2010; Conley and Udry, 2010; Wollni et al., 2010; Dercon and Christiaensen, 2011; Teklewold et al., 2013). Among the studies conducted in Ethiopia, Dercon and Christiaensen (2011) find that lack of insurance or alternative consumption smoothing mechanisms lead farmers to make less investment in new agricultural technologies. Alem et al. (2010) also documented that rainfall variability raises the risk and uncertainty of inorganic fertilizer use, while abundant rainfall in previous years relaxes the liquidity constraints and affordability of fertilizer in the Central Highlands of Ethiopia. While these are the common factors limiting farmers'transition from the state of non-adoption to adoption, Doss (2006) highlighted the need for study of the continued use of agricultural technologies following initial adoption.

Disadoption is an important issue in the study of agricultural technologies adoption in helping to identify factors that boost long-term adoption/use of technologies. Neill and Lee (2001) documented that farmers in Honduras disadopt the practice of legume-maize crop rotation at a rate of 10% per year due to emergence of weed species that increase labor requirements. This increased labor requirement has also been noted as a reason for the disadoption of the Systems of Rice Intensification (SRI) in Madagascar (Moser and Barrett, 2006). Moreover, Marenya and Barrett (2007) also find that farm size, value of livestock owned, off-farm income, family labor supply, educational attainment, and female household head are significant factors in discouraging farmers'use of integrated natural resource management practices in Western Kenya. Further, Wendland and Sills (2008) document that household preference, resource endowments, risk and uncertainty affect households decisions on continued use of soybeans in Togo and Benin.

Building on the few existing agricultural technology disadoption studies (e.g., Neill and Lee, 2001; Moser and Barrett, 2006; Marenya and Barrett, 2007; Wendland and Sills, 2008), the contribution of the current study is twofold. First, using plot level data on adoption and disadoption of multiple technologies, namely, chemical fertilizer, improved seed, manure and soil conservation methods, we investigate the driving forces of the disadoption of multiple interrelated agricultural technologies. Due to lack of data on the disadoption of multiple agricultural technologies, most of the few previous studies (with the exception of Marenya and Barrett, 2007) have focused on the disadoption of a single technology in isolation. Analysis of disadoption of a technology without controlling the adoption and disadoption of other interrelated technologies could cause bias, inconsistency and inefficiency of parameter estimates (Greene, 2008). Unlike Marenya and Barrett (2007), we control for soil and other plot-related characteristics and additional socio-economic characteristics such as risk and time preference that could impede the continued use of the technologies. Furthermore, we have more than six times the sample size of Marenya and Barrett (2007), which provides an advantage in improving the precision of the estimated parameters.

Second, unlike previous studies, we analyze whether the adoption/disadoption of the green revolution techniques is related to the adoption/non-adoption of other sustainable land management practices. Agronomics literature and a few economics studies have documented complementarity of the green revolution techniques with these other sustainable land management practices (Marenya and Barrett, 2009; Chivenge et al., 2011). Application of manure and/or soil conservation enhances the organic components and water holding capacity of soil. These organic components and water holding capacity are important elements to facilitate the decomposition and release of nutrients when inorganic fertilizer is applied to the soil. However, this complementarity result is from an agronomical controlled trial experiment. The real world is different from the controlled trial experiment. Usually farmers'behavior deviates from controlled trial experiment results; agricultural economists study why this happens. This paper is one of the behavioral studies that asks whether farmers choice of these technologies and practices show substitutability or complementarity in adoption/disadoption decisions.

Due to liquidity constraints, risk, or lack of knowledge about the complementary nature of the inputs, farmers may perceive that the application of manure or soil conservation can substitute for the use of green revolution technologies. For example, farmers may perceive that manure and soil conservation practices, like chemical fertilizer, increase soil fertility, though each is adding different nutrients to the soil. Those who use manure or soil conservation may be less likely to adopt and use inorganic fertilizer. Likewise, due to these and other reasons, farmers may disadopt the inorganic fertilizer and replace it with manure or soil conservation. For example, in an area where there is erratic and meager rainfall, and where the plot's soil type lacks important minerals and nutrients, application of inorganic fertilizer can make the seedling or crop "burn"[1] by raising the acidity of the soil. Farmers who experienced this negative effect of inorganic fertilizer may disadopt the inorganic fertilizer and replace it with manure or soil conservation. The above examples are explanations of how farmers can perceive the green revolution techniques as substitutes with other sustainable land management practices in adoption/disadoption decisions.

On the other hand, farmers'choices for these technologies can also be complementary in adoption/disadoption decisions. Farmers who know about scientifically proven complementarity and those who have the access and capacity to buy the green revolution technologies may use green revolution technologies with farmyard manure and/or soil conservation. These farmers are most likely to reap the benefit of the mix and are less likely to disadopt green revolution technologies. For these farmers, green revolution technologies and other sustainable land management prac-

[1]When there is not sufficient rainfall or moisture in the soil, application of chemical fertilizer (UREA and DAP are types of fertilizer available in the study area) will make the seedling or crop die (burn) due to the acidic nature of these fertilizer types

tices are complementary in adoption/disadoption decisions, i.e., for such farmers, there may be no difference between perceived and actual substitutability and complementarity of the technologies. Which of the above behaviors prevails is an empirical issue and the substitutability and complementarity results may not be symmetric between adoption and disadoption decisions.This is because in disadoption farmers have some experience with the technologies. Over time, farmers'knowledge about the technologies and other constraints might differ, thus potentially affecting the decision process and subsequently affecting nature of the substitutability and complementarity of the technologies. There exist few studies that test the relationship of green revolution technologies with these other sustainable practices in disadoption decisions. In this study, the data on the disadoption of green revolution technologies can help us understand the relationship among the technologies and practices in disadoption decisions. We used both fixed and random effects linear and nonlinear simultaneous equations methods with Mundlak specifications to answer our research questions.

Our results indicate that farmers who apply green revolution technologies in plots with black/brown soil type, plots that are not sloping, plots that are near the farmer's homestead and near extension centers, and plots that have access to water are less likely to disadopt the green revolution technologies. We also find that farmers who use farmyard manure and/or soil and water conservation methods are less likely to adopt inorganic chemical fertilizer. In the transition from the state of non-adoption to the state of adoption of inorganic fertilizer, farmers perceive farmyard manure and/or soil and water conservation practices as substitutes for inorganic fertilizer. However, farmers who use a mix of inorganic fertilizer and farmyard manure and/or soil and water conservation methods are less likely to disadopt the green revolution technologies. Our results also indicate that improved seed varieties and inorganic fertilizer are complementary in both adoption and disadoption decisions, implying that the disadoption of one leads to disadoption of the other.

The rest of paper is organized as follows. Section two introduces the conceptual framework and empirical strategy of our study. In section three, we describe the data source and study area. Sections four and five present descriptive statistics and econometric results, respectively. Finally, the last section concludes.

2 Conceptual framework and empirical strategy

Farmers'adoption and disadoption decisions for a single technology or multiple technologies as a package can be modeled using a random utility framework. Let U_j^n be the benefit in the state of non-adoption (n) of a technology (or package of technologies)j , U_j^a be the benefit in the state of adoption (a) and U_j^d be the benefit in the state of disadoption (d). Farmer i decides to transit from the state of non-adoption to the state of adoption of a technology (or a package) j on plot p if Y_{ipj}^*=U_{ipj}^a - U_{ipj}^n $>$ 0 and decides to disadopt if Y_{ipj}^*=U_{ipj}^d - U_{ipj}^a $>$ 0 , where Y_{ipj}^* is the latent net benefit of adopting or disadopting a technology (package of technologies) . This latent adoption/disadoption decision is determined by:

$$Y_{ipj}^* = X_{ipj}\beta_j + \epsilon_{ipj} \tag{1}$$

$$\epsilon_{ipj} = \alpha_{pj} + \eta_{ij} \tag{2}$$

where X_{ipj} represents a vector of observed farmer i and plot p characteristics for adoption/disadoption of technology j [j=chemical fertilizer adoption (F^a), chemical fertilizer disadoption (F^d), improved seed adoption (V^a), improved seed disadoption (V^d), manure adoption (M^a) and soil conservation (S^a)], and β_j is a vector of unknown parameters for the j^{th} technology adoption/disadoption equation. ϵ_{ipj} is the composite error term, which consists of α_{pj} , plot-specific unobserved characteristics, and η_{ij} , unobserved individual farmer characteristics. Because the latent (unobserved) net benefit of adopting or disadopting technology j is unobservable, equation 1 is mapped to an observable binary variable Y_{ipj} indicating whether or not a farmer is adopting or disadopting technology$j$:

$$Y_{ipj} = \begin{cases} 1 & if\, Y_{ijp}^* > 0 \\ 0 & if\, Y_{ijp}^* \leq 0 \end{cases} \tag{3}$$

Because we have plot-varying information for every farmer and each has more than one plot, we can treat this data as a pseudo-panel data set and apply the usual fixed and random effects estimation methods of panel data. However, given that the socio-economic characteristics of farmers are plot-invariant, the application of the fixed effects method eliminates both observed and unobserved farmer-specific socio-economic characteristics. This means that estimates of plot-varying characteristics are free of bias from unobserved plot-invariant characteristics; however, one will not be able to identify the parameters of socio-economic characteristics. In order to identify the estimates of observable socio-economic characteristics, the random effect method can be applied. This model assumes that plot-invariant unobserved characteristics are independent of the observable plot and socio-economic characteristics. This is, however, unlikely because some of the plot-invariant characteristics, such a farmer's motivation or ability, may be correlated with some of the regressors in the model, such as education. To correct for this, we used the correlated random effects method, following Mundlak (1978), which involves including the averages of time-varying regressors (plot-varying, in this case) in the model. This method also controls the bias from plot-invariant unobserved characteristics. In the literature, this method is also called pseudo-fixed effects (e.g., Di Falco et al., 2012). To ensure robustness, we estimate both models and discuss the results.

Further, if we assume the error terms are independently and identically distributed across technologies for both adoption and disadoption decisions, equations 1 and 3 represent four separate adoption models and two disadoption models (for fertilizer and improved seed). This assumes no interdependency among the technologies and no correlation between adoption and disadoption decisions. However, a farmer may adopt two or more technologies simultaneously or the adoption of one technology may be conditioned on his/her adoption of another technology, either because they are substitutes or complements. Moreover, the transition of households across discrete states of adoption and disadoption is more likely to cause a correlation between the unobservable error terms of the two decisions, because the disadoption decision is contingent on the adoption decision. That is, farmers make two discrete interrelated decisions. First, households decide whether to adopt a new technology (a package of technologies). Once farmers adopt that technology (the package), they decide either to continue or discontinue using it. A single equation estimation approach could cause bias and inefficiency in the parameters if the interdependence is observed and/or if unobserved heterogeneity is correlated among these technologies in both adoption and disadoption decisions (Greene, 2008). A Multivariate Probit method (MVP) (non-linear seemingly unrelated simultaneous equation) and a linear seemingly unrelated simultaneous equation model (SURE) that allow correlation among the unobserved disturbances are best suited to the adoption and disadoption decisions for interrelated agricultural technologies and practices.

Following Teklewold et al. (2013) and Ndiritu et al. (2014), interdependence of technologies in both adoption and disadoption decisions can be tested by looking at the sign and significance of the off-diagonal elements of the variance-covariance matrix, Σ , of a Multivariate Probit Model (MVP) or SURE model, where Σ ;

$$\Sigma = \begin{bmatrix} 1 & \rho_{F^aF^d} & \rho_{F^aV^a} & \rho_{F^aV^d} & \rho_{F^aM^a} & \rho_{F^aS^s} \\ \rho_{F^dF^a} & 1 & \rho_{F^dV^a} & \rho_{F^dV^d} & \rho_{F^dM^a} & \rho_{F^dS^s} \\ \rho_{V^aF^a} & \rho_{V^aF^d} & 1 & \rho_{V^aV^d} & \rho_{V^aM^a} & \rho_{V^aS^s} \\ \rho_{V^dF^a} & \rho_{V^dF^d} & \rho_{V^dV^a} & 1 & \rho_{V^dM^a} & \rho_{V^dS^s} \\ \rho_{M^aF^a} & \rho_{M^aF^d} & \rho_{M^aV^a} & \rho_{M^aV^d} & 1 & \rho_{M^aS^s} \\ \rho_{S^aF^s} & \rho_{S^aF^d} & \rho_{S^aV^a} & \rho_{S^aV^d} & \rho_{S^aM^a} & 1 \end{bmatrix} \tag{4}$$

and $\rho_{jj'}$ is the correlation coefficient betweenϵ_{ipj} and $\epsilon_{ipj'}$.

3 Data and description of study area

The study is conducted in twelve villages of southern Tigrai, Ethiopia, using a total of 597 sample households and 1344 plots that represent the major agro-ecological conditions of the country.[2] The survey was conducted during July-October 2013 by the author through the Environmental Economics Unit of the University of Gothenburg, Sweden, in cooperation with the Department of Economics of Mekelle University, Ethiopia. The main aim of the data collection was to study intra-household decisions and adoption/disadoption of clean cookstoves and agricultural technologies. Questions about adoption and disadoption of multiple agricultural technologies were included in this survey to study the determinants and interlinkage of agricultural technologies and practices in adoption and disadoption decisions

A total of 600 sample households were randomly selected from 12 villages (kushets) in a region that represents weather conditions that are common in Ethiopia. We randomly selected 50 households from each village using a list of households obtained from each village's administrator.

[2]The region contains the Dega, Weynadega and Kola agro-ecological zones. Kola, at an altitude between 500-1500 meters above sea level (m.a.s.l), is characterized by a relatively hotter and drier climate, whereas Weynadega (15002500 m.a.s.l) and Dega (25003500 m a.s.l) are wetter and cooler (Deressa et al., 2009).

The survey was conducted using a group of 15 enumerators, one supervisor, and 7 village cadres, in one village at a time. All fifteen enumerators interviewed all fifty subjects in most villages, except in two villages, where 48 and 49 households were interviewed.[3] On average, the survey questions took 1.45 hours per household. In the survey, households were asked about their socio-economic characteristics, fuel use, cooking practices, adoption and disadoption of agricultural technology, household decision-making power, etc.

The study area is located in the northern part of the country, with annual rainfall averages between 450 and 600 mm and annual temperature between 16 and 26^oC. It is an area with a mixed farming production system. Food and cash crop cultivation are practiced, along with livestock rearing. Farming activities depend on the February to May Belg rains and the July to September Kiremti rains. The main crops cultivated are sorghum, teff, wheat, and barley. Barley and wheat are cultivated mainly in the Dega and Weynadega agro-ecological zones, while teff and sorghum are mainly cultivated in the Kola agro-ecology zone. Barley and wheat are the staple foods in the Dega and Weynadega agro-ecological zones, while sorghum is the staple food in the Kola region. Teff is produced by farm households for both own consumption and market sale. Land preparation is done using oxen draught power. Cattle, goats and sheep are reared in the zone. Livestock are important as a source of draught power, income and food and also to produce manure for agriculture. Other important economic activities in the zone are local agricultural labor, petty trading and salt trading.

4 Descriptive statistics

Table 1 of Appendix A provides summary statistics of the variables in the multivariate probit and SURE regression analysis. These variables were selected following earlier studies on agricultural technology adoption decisions (e.g., Pender and Kerr, 1998; Shiferaw and Holden, 1999; Marenya and Barrett, 2007; Yesuf and Khlin, 2009; Kassie et al., 2009, 2010, 2013; Teklewold et al., 2013).

[3]Two weeks before we conducted the baseline survey, the village leader and village cadres received a list of households selected for the survey. The cadres and leaders asked households if they would be available at the time we planned to conduct the survey in the village. If they would not be available, the cadres were told to replace them with the next neighbor. Because there was payment for the study, we surveyed most of the households at the appointed time. However, three households for which appointments were scheduled were not available.

We present the descriptive statistics of the variables under three headings: plot characteristics, farmers socio-economic characteristics, and technology variables.

The plot-specific characteristics include soil type, plot slope, plot level experience in applying fertilizer, experience in applying improved seed, and land ownership type. Farmers in the study area traditionally classify the soil type as $w$alka, $k$eyehtay, and $s$heshher, These three soil types differ in their color, water holding capacity, and organic and mineral content. Walka is mostly black or brown (vertisol), with higher water holding capacity and relatively more organic materials in the soil, and is classed as relatively fertile soil (Elias and Fantaye, 2000; Woldeab, 2003; Abebe, 2007). Keyehtay is a reddish, non-vertisol and non-sandy soil, with less organic material in the soil and relatively lower water holding capacity, and is classed as relatively less fertile than $w$alka soil. Sheshher is sandy soil which is the least fertile and has the least water holding capacity and the least organic materials (Elias and Fantaye, 2000; Woldeab, 2003; Abebe, 2007). Water holding capacity and organic components of soil are important elements to facilitate the decomposition and release of nutrients when inorganic fertilizer is applied to the soil (Chivenge et al., 2011).

The water storage capacity of soil is typically important in regions with uncertain rainfall (e.g., the study area) and farmers can take into account this aspect of soil composition in the decision to adopt inorganic fertilizer. Furthermore, while the black ($w$alka) soil type is generally classified as less acidic, the reddish ($k$eyehtay) and sandy soil ($s$heshher) types are generally classified as acidic (Abebe, 2007). This is also an important element in the decision to adopt and disadopt chemical fertilizer. In the study area, farmers have been advised by agricultural extension workers to simply adopt and use the same type of chemical fertilizer without measuring acidity or the nutrient requirements of the soil. This has implications for the disadoption of chemical fertilizer. Generally, application of chemical fertilizers increases the acidity of the soil and this will be more problematic if the soil is naturally acidic. The burning potential of chemical fertilizer is high when it is applied in naturally acidic soil. Therefore, farmers with this type of soil are more likely to disadopt chemical fertilizer. In the study area, a large proportion of the soil type is $k$eyehtay (47%) and $s$heshher (28%), which implies a high risk of disadopting chemical fertilizer if farmers do not adopt other land/soil management practices (Ano and Ubochi, 2007).

(Table 1 about here)

The slope of the plot is an indicator of soil erosion potential (Lapar et al., 1999; Bekele and Drake, 2003). Plot slope is expected to positively influence the soil conservation decision; farmers are more likely to adopt both green revolution technologies (chemical fertilizer and improved seed) and farmyard manure if their plots have less slope, and are less likely to disadopt green revolution technologies in plots with less slope. In our data set, the variable plot slope is measured based on farmers'own perceptions of the slope of their plot on a 4-point scale, where 1 means flat and 4 means very sloping. On average, plots in the study area are less sloping (mean value of 1.45).

The incentives for farmers to invest in new technologies depend on whether the plot is owned by the farmer or rented in from other farmers. We expect a farmer to give greater care to his own farm land than to land which is rented in. In addition, the number of years a farmer has been applying improved seed and chemical fertilizer can be a good indicator of success in adoption. Those with longer years of experience in using the technologies are expected to have learned how to improve productivity using these technologies and are less likely to disadopt. Farmers in the study area do not have long years of experience in farming with green revolution technologies; the average experience with fertilizer and improved seed is 5 and 3.5 years, respectively.

Following the literature, in our random effect specifications, we also control for time preference, risk preference and socio-economic conditions of farm households, such as age of the household head, education, wealth and number of livestock owned. Wealth is measured by the value of assets owned by the household.

We use hypothetical risk and time preference questions to measure farmers'subjective time and risk preferences. To measure the time preference, we asked the farmers to make four choices between immediate money and varying amounts of delayed money. To reduce the cognitive burden and fatigue, we kept the payment delay constant across the questions and asked them to make only four choices, as shown in Appendix B. From these alternatives, we construct a time preference variable that ranges from zero to four, where zero refers to the most patient and four is the most impatient. Zero corresponds to a farmer's preference for 5500 Ethiopian Birr (ETB)[4] after one year to 5000 ETB today, while four represents a farmer's preference to have 5000 ETB today and unwillingness to wait at all. Our risk preference variable is also constructed from survey questions where farmers were asked to choose a preferred lottery from five hypothetical lotteries, each with

[4]The exchange rate during the study period was 1 USD= 18.85 ETB.

an equal chance of winning, as shown in Appendix B. From these alternatives, we construct a risk preference variable that ranges from zero to four, where zero is the most risk averse and four is the least risk averse. Zero corresponds to a farmer's preference for ETB 250 without any risk, while four represents a choice of the lottery that gives either 1000 ETB or nothing, each with a 50% chance of winning.

The variables under the technology section include the adoption and disadoption of chemical fertilizer, improved seed, and manure and soil conservation methods. Each of these six technology variables represents the dependent variables of simultaneous equation models presented in the earlier section. The adoption of chemical fertilizer and improved seed varieties are dummy variables taking a value of one if the farmer used each of the technologies in each of the plots for the Mehar season of the 2006 Ethiopian calendar (E.C.). Table 1 shows that around 53% and 38% of the plots in the study area used chemical fertilizer and improved seed varieties, respectively, in the 2006 E.C. Mehar season.

Likewise, adoption of manure and soil conservation methods (soil bunds, stone bunds, trees/grasses on plot boundaries) are dummy variables taking a value of one if the farmer applied these practices in each plot for the Mehar season of 2006 E.C. or earlier. From Table 1, we can see that that around 25% and 51% of the plots in the study area used manure and soil conservation methods, respectively. These reported adoption rates are comparable to earlier adoption studies in Ethiopia and other African countries (e.g., Marenya and Barrett, 2007; Yesuf and Khlin, 2009; Kassie et al. 2009, 2010, 2013; Teklewold et al., 2013; Ndiritu et al., 2014). On the other hand, the disadoption of chemical fertilizer and improved seed varieties are also dummy variables taking a value of one if the farmer totally stopped using each of the technologies in each plot on or before the Mehar season of 2006 E.C. From Table 1, we can also see that around 32% and 18% of the plots in the study area have disadopted inorganic fertilizer and improved seed varieties, respectively. Moreover, from Table 2, one can see that 75% of farmers who disadopted inorganic fertilizer did so due to risk of low yield because previous trials were not successful due to crop burn/low yield with a low amount of rainfall, while 31% of those who disadopted improved seed did so because of an insignificant yield and income difference between improved and traditional seed.

(Table 2 about here)

Following Ramful and Zhao (2009) and Teklewold et al. (2013), we use simple descriptive conditional and unconditional probabilities of adoption and disadoption to show the symmetry of relationships between green revolution technologies and other land management practices in adoption and disadoption states. Starting our analysis with the relationship between chemical fertilizer and manure in farmers technological choices, Table 3 of Appendix A shows that the probability of adopting (choosing) chemical fertilizer decreases from 53% (the unconditional take-up rate) to 35% when manure is applied to the plot. Similarly, the probability of adopting manure decreases from 25% to 16% when chemical fertilizer is applied to the plot, suggesting that farmers perceived chemical fertilizer and manure as substitutes in the transition from the state of non-adoption to the state of adoption.

(Tables 3 and 4 about here)

However, we observe a difference in the transition from the state of adoption to the state of disadoption of inorganic fertilizer. As shown in Table 3 of Appendix A, the disadoption rate increases from 32% (unconditional disadoption rate) to 42% when farmers do not use manure and decreases to 2% when farmers apply manure to their plots. This suggests that the use of manure significantly reduces the disadoption of chemical fertilizer and implies the complementarity of the two inputs in the disadoption of chemical fertilizer. This result is consistent with the literature in plant science and a few economics literature that the integrated use of farmyard manure and chemical fertilizer sustains the health of the soil, increases the efficiency and uptake of nutrients from chemical fertilizer, balances soil acidity, and hence improves the productivity of fertilizer (Kramer et al., 2002; Satyanarayana et al., 2002; Bayu et al., 2006; Marenyan and Barrett, 2009; Chivenge et al., 2011). We also observe a similar difference in the substitutability and complementarity between chemical fertilizer and soil conservations methods in the adoption and disadoption states (see Tables 3 and 4).

Unlike the result with chemical fertilizer, we do not see a difference in the substitutability and complementarity of improved seed with manure and soil conservation methods in either adoption or disadoption decisions. From Table 3, we can see that the adoption rate increases from 38% (unconditional uptake) to 61% when manure is applied and 59% when a soil conservation method is applied. From Table 4, we also observe that the rate of disadoption of improved seed increases from 18% (unconditional disadoption rate) to 22% when manure is not applied and also increases from 18% to 22% when a soil conservation method is not applied. Conversely, the unconditional disadoption rate decreases from 18% to 9% when manure is applied and decreases from 18% to 15% when a soil conservation method is applied (see Table 4). This result suggests complementarity of improved seed with both manure and soil conservation methods in the decision to transit from non-adoption to adoption and adoption to disadoption states.

Regarding the interdependence of fertilizer and improved seeds, we observe that the uptake of chemical fertilizer increases from 53% (unconditional uptake) to 66% when improved seed is adopted. Likewise, the uptake of improved seed increases from 38% (unconditional uptake) to 48% when chemical fertilizer is adopted (see Table 3). From the disadoption side (Table 4), it can be seen that the rate of unconditional disadoption of chemical fertilizer increases from 32% to 65% when improved seed is disadopted and the rate of unconditional disadoption of improved seed increases from 18% to 37% when chemical fertilizer is disadopted. This descriptive statistics result may imply that farmers simultaneously adopt both fertilizer and improved seed as a package and that the two inputs are complementary in both adoption and disadoption decisions.

5 Econometrics results

MVP and SURE results: Interdependencies and determinants of disadoption of green revolution technologies

Results from the maximum likelihood estimation of the correlated random effect MVP are presented in Table 5. The Wald chi-square (χ^2) test statistics presented in Table 5[$\chi^2(195) = 1987.51, prob > \chi^2 = 00$] indicate the fitness of the Multivariate Probit (MVP) Model with the data and the relevance of the chosen explanatory variables in explaining the model. The likelihood ratio test result confirms not only the existence of the correlation between adoption and disadoption decisions but also the existence of interdependencies among agricultural technologies in both adoption and disadoption decisions. In addition, the mean values of plot-varying covariates are jointly significant, implying the relevance of the Mundlak approach in controlling the bias from unobserved plot-specific factors.

(Table-5 about here)

The likelihood ratio test of independence tells us the existence of interdependence without showing the type of relationship or interdependence among these technologies. The type of relationship can be shown through the signs of the correlation coefficients of the models (Table 5) (Teklewold et al., 2013; Ndiritu et al., 2014). Starting our analysis with the results of the interdependence between chemical fertilizer and other land management practices (soil conservation and farmyard manure), in line with the descriptive statistics results, we observe that their relationship is asymmetric in adoption and disadoption decisions. For example, looking at the estimates of correlation coefficients of the MVP model (Table 5), we observe that inorganic fertilizer has negative and significant correlation with manure and soil conservation $[\rho_{F^aM^a} = -40\%]$ and $[\rho_{F^aS^s} = -25\%]$. These negative correlations may indicate farmers'substitution of inorganic fertilizer (green revolution technology) with manure and soil conservation methods, despite the fact that green revolution technology and the aforementioned sustainable land management practices are complementary in production. Farmers may substitute green revolution technology with these sustainable land management practices due to liquidity constraints, labor market constraints, risk preference and lack of knowledge about the complementary nature of these techniques. As shown in Table 5, wealth, participation in off-farm activities, education and risk preferences of the farmers are significant determinants of adoption of this green revolution technology. These results are consistent with the findings of Yusuf and Köhlin (2009) and Teklewold et al. (2013).

In the disadoption decision, the correlations are still negative and significant $[\rho_{F^dM^a} = -20\%]$ and $[\rho_{F^dS^a} = -12\%]$. These negative correlations, however, may indicate complementarity of inorganic fertilizer with manure and soil conservation, which is consistent with the complementary nature of the inputs. This means that farmers who combine inorganic fertilizer with both manure and soil conservation methods may be less likely to disadopt and may also be more likely to reap the benefit of combining these inputs. This is consistent with the findings in plant science (Kramer et al., 2002; Satyanarayana et al., 2002; Bayu et al., 2007; Chivenge et al., 2011) and economics literature (Marenya and Barrett, 2009).

Unlike the case of inorganic fertilizer, the relationship of improved seed varieties with manure and soil conservation is not different in adoption and disadoption decisions. As shown in Table 5, improved seed is complementary with both soil conservation methods and manure in both adoption and disadoption decisions [($\rho_{V^aM^a} = 34\%; \rho_{V^aS^a} = 56\%$), ($\rho_{V^dM^a} = -18\%; \rho_{V^dS^a} = -21\%$)]. Farmers are more likely to adopt and less likely to disadopt improved seed when these other land management practices are also implemented on the plot. While inorganic fertilizer can be a close substitute for manure and soil conservation methods in terms of investments to improve a plot's soil fertility, improved seed cannot be a close substitute for manure and soil. However, one may argue that farmers who are resource (liquidity) constrained or risk averse may substitute improved seed for manure and soil conservation to pursue the overall goal of higher yield. Nonetheless, as can be seen from Table 5, we do not find liquidity constraints, labor market constraints or risk factors as significant determinants of improved seed adoption. This may be because improved seed is not as expensive as inorganic fertilizer and can be bought in a small quantity (e.g., 5 kg maize per timad, which equals 1/4 hectare), while inorganic fertilizer is sold in bulk (at least a 50 kg/sack). Knowledge about improved seeds (proxied by education and distance to extension center) and experience in farming with improved seed are found to be strong correlates of adoption and disadoption of improved seed varieties.

From the estimated correlation coefficients (Table 5), we can also see that inorganic fertilizer and improved seed varieties are complementary in both adoption and disadoption decisions. This complementarity in adoption may imply the take-up of the two green revolution techniques as a package. Furthermore, the positive and significant correlation (Table 5) of the disadoption of the two green revolution technologies could further strengthen take-up of the inputs as a package. However, compared to the long time during which extension services have been available (more than 20 years), the reported percentage (20%) of complementarity is still low. This is consistent with earlier studies in the same country (e.g., Teklewold et al., 2013) and neighboring countries (e.g., Ndiritu et al., 2014).

Looking at the estimates of determinants of adoption and disadoption of green revolution technologies and the aforementioned other sustainable land management practices [Table 5], it can be seen that farmers with *walka*(brown/black) soil are more likely to adopt and less likely to disadopt inorganic fertilizer, which implies that farmers are aware of the compatibility of inorganic fertilizer with this soil type. We observe a similar relationship between the *walka* soil type and disadoption of improved seed varieties. However, we observe a negative relationship between the *walka* soil type and the application of soil conservation methods. Farmers are more likely to apply soil and water conservation methods to *keyehtay* and *sheshher* soil types than to black and brown soil types. This result may also imply that *keyehtay* and *sheshher* are more vulnerable to soil erosion and that farmers are doing more soil and water conservation activities in plots with these soil types, but the result for manure is not significant.

As expected, the plot slope variable is negatively related with the application of both green revolution technologies and farmyard manure. However, it is positively and significantly related with soil and water conservation methods and disadoption of green revolution technologies. Further, distance of the plots from the homestead is negatively correlated with adoption of green revolution technologies and these other land management practices and is related positively with disadoption of green revolution technologies. This implies that higher transport and monitoring costs are among the reasons for disadoption of green revolution technologies and non-adoption of other sustainable land management practices. Water availability (proxied by access to irrigation) and tenure security (proxied by owned or rented plot) are a significant determinant of adoption and disadoption of green revolution technologies.

With regard to farmers'socio-economic characteristics, it can be seen that farmers who have had experience in farming with green revolution technologies are less likely to disadopt these technologies. This implies that farmers who adopt for a longer period of time might have learnt how to use these green revolution technologies effectively and efficiently and hence they are more likely to reap the benefit of using these technologies. From Table 5, it can also be seen that risk preference is a significant determinant of both adoption and disadoption of inorganic fertilizer; however, it is insignificant in the adoption of improved seed. The significance of risk in the adoption of inorganic fertilizer may be attributed to the burning potential of inorganic fertilizer and the uncertainty of rainfall. This means that only those who are not risk averse are more likely to adopt inorganic fertilizer. On the disadoption side, the significance of the risk preference variable may imply a change in the risk aversion behavior of farmers over time; in other words, the use of inorganic fertilizer may reduce risk-taking behavior. However, we find the opposite for the time preference variable in the adoption and disadoption of improved seed varieties. The results also show that more patient households are more likely to apply manure and soil conservation practices. Education is positively related to adoption and negatively related to disadoption of green revolution technologies practices. Distance to extension center (a proxy for access to agricultural innovations and practices) is negatively related to adoption and positively related to disadoption of both green revolution technologies.

Robustness checks

An alternative method to control for unobserved heterogeneity is to use the standard fixed effects estimator. This estimator relies on data transformation, whereby variables are transformed into deviations from their means. Because estimation of standard fixed effects for an MVP is not possible[5] , a standard fixed effects model is estimated for the linear multivariate model (SURE Model). Linear probit models are convenient and computationally tractable for estimating marginal effects, and some empirical literature has documented that there is an insignificant difference between linear and non-linear marginal effects (Angrist and Pischke, 2009, pp. 94-107). Therefore, standard linear fixed and correlated random effects multivariate models are estimated to check the robustness of our results in terms of sign and significance of the coefficients. Tables 6 and 7 in Appendix A present the correlated random effect and standard fixed effects estimates, respectively.

(Tables 6 and 7 about here)

Like the correlated MVP Model estimated above, the χ^2 test statistics and Breusch-Pagan test results also confirm the relevance of the chosen explanatory variables, interdependencies among technologies, and appropriateness of the Mundlak approach in controlling the bias from unobserved plot-specific factors. Further, the estimated correlation coefficients of unobserved error terms in both linear correlated random effects and standard fixed effects estimates are comparable to the sign and magnitude of the correlation coefficients of the MVP Model. Similarly, the sign and significance of plot and socio-economic characteristics of the linear correlated random effects and the standard fixed effects estimates are mostly comparable to estimates of MVP.

The consistency of linear and non-linear as well as random and fixed effects simultaneous equation estimates of correlations of farmers'technological choices implies robustness of the above results. In all the models, consistent with the results of descriptive statistics, manure and soil

[5]Because MVP is a family of the probit model which uses the CDF of the standard normal distribution in the likelihood function, it is impossible to use the fixed effects transformation (Green, 2008; Wooldridge, 2010).

conservation practices are substitutes with inorganic fertilizer in adoption decisions, while manure and soil conservation are complementary in disadoption of inorganic fertilizer. The burning effect can be reduced by application of farmyard manure, long-term application of crop residuals, or soil and water conservation methods (Kramer et al., 2002; Satyanarayana et al., 2002; Bayu et al., 2007; Ano and Ubochi, 2007; Chivenge et al., 2011). In the study area, as can be seen from Table-2, 75% of farmers who disadopted inorganic fertilizer pointed out a risk of crop burning as their main reason for the disadoption of chemical fertilizer. This may have an effect on disadoption of other complementary inputs. For example, in the study area, farmers who disadopt inorganic fertilizer are at least 14% more likely to disadopt improved seed.

6 Conclusion

Since the advent of the Asian green revolution, there has been hope that the use of green revolution technologies in sub-Saharan Africa would curb undernourishment and create the foundation for sustainable growth. However, crop productivity has not been significantly increased and undernourishment has declined by only an insignificant amount. This could be due to the low rate of adoption of these green revolution technologies and due to the fact that farmers have been offered the same type of technology without testing the differing nutrient requirements and acidity of their soil. As a result, some farmers do not continue to use these technologies. Using a sample of 1344 plots and 597 farm households, this paper studies the driving forces for the disadoption of two green revolution technologies. The paper also studies the relationship between green revolution technologies and other sustainable land management practices such as soil conservation practices and farmyard manure in adoption and disadoption decisions. We use fixed and random effects linear and non-linear econometric methods to answer these questions.

From both the descriptive and econometric results, we find that farmers who use farmyard manure and/or soil conservation practices are less likely to adopt inorganic chemical fertilizer. In the transition from the state of non-adoption to the state of adoption of inorganic fertilizer, farmers perceive soil and water conservation practices and/or farmyard manure as substitutes for inorganic fertilizer. Farmers may substitute this green revolution technology with these other sustainable land management practices due to liquidity constraints, labor markets constraints, risk preference and lack of knowledge about the complementary nature of these inputs. These results are consistent with the findings of Yesuf and Khlin (2009) and Teklewold et al. (2013). However, farmers who use a mix of inorganic fertilizer and these other land management practices are less likely to disadopt the modern technology and are more likely to reap the benefit of the mix. Farmers who use the inorganic fertilizer without applying other sustainable land management practices are more likely to disadopt inorganic fertilizer.

With regard to improved seed, we find that it is complementary with soil and water conservation practices and farmyard manure in both adoption and disadoption decisions. Unlike inorganic fertilizer, we do not find liquidity or labor constraints as significant determinants of improved seed adoption or as factors that causes farmers to substitute improved seed with these other land management practices. This may be because improved seed is not as expensive as inorganic fertilizer and can be bought in a small quantity, while inorganic fertilizer is sold in bulk. Knowledge about improved seed (proxied by education and distance to extension center) and experience farming with improved seed are found to be significant determinants of adoption and disadoption of improved seed varieties. Unlike the finding of Teklewold et al. (2013), in our study area, we find complementarity of improved seed with these other land management practices.

Our results indicate that farmers who apply green revolution technologies in plots with black/brown soil type are less likely to disadopt the green revolution technologies. This result is consistent with the literature in plant science, which finds that black/brown soil has relatively higher organic components and higher water holding capacity. Water holding capacity and organic components of soil are important elements to facilitate decomposition, normalize acidity and release nutrients when inorganic fertilizer is applied to the soil. This particularly fits the following two conditions in the study area. First, the study area is subject to frequent drought and erratic rainfall. Second, farmers in this region are offered the same type of inorganic fertilizer without testing the differences in nutrient requirements and acidity of their soil. In line with this, we find that risk averse farmers are less likely to adopt inorganic fertilizer. This could be attributed to the burning potential of inorganic fertilizer with insufficient rainfall. We also find that disadoption of green revolution technology is more common on rented plots, plots placed far from the homestead, and plots with steep slope with no application of soil conservation methods.

Consistent with the findings of Teklewold et al. (2013) and Ndiritu et al. (2014), we find that improved seed varieties and inorganic fertilizer are complementary, implying take-up of both inputs as a package. However, considering the long years of effort of agricultural extension workers, the rate of complementarity is not large. We also find complementarity on the disadoption side. Farmers who disadopt inorganic fertilizer are more likely to disadopt improved seed. However, this simultaneous disadoption can be reduced if farmers use a mix of green revolution techniques and other sustainable land management practices. This result implies that agricultural extension workers can expand their work, not only to propagate the take-up of green revolution technologies as a package but also to encourage a mix of these technologies and other sustainable land management practices such as soil and water conservation practices and/or farmyard manure.

However, this paper is not without limitations. The paper estimates the substitutability and complementarity of the technologies in adoption and disadoption decision through the correlation of error terms. Due to lack of exogenous instruments in the data, we have not incorporated each technology as a determinant of the other technology in each of the adoption and disadoption equations. Estimates of substitutability and complementarity in technologies based on correlation of error terms are subject to omitted variable bias and hence our estimates are correlations, not causal relationships. Further, the disadoption of agricultural technologies may be better dealt with using multiple rounds of panel data and dynamic panel data models. Therefore, future research can investigate substitutability and complementarity of multiple agricultural technologies in adoption and disadoption decisions with exogenous instruments and with many years of panel data where the time gap between the rounds is long enough to reveal the dynamics. However, even in the absence of such panel data, the current paper sheds light on how farm households disadopt interrelated technologies and the relationships among technologies in adoption and disadoption decisions.

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Appendix A: Tables of descriptive statistics and regression results

Table 1: Descriptive statistics of individual and household characteristics(one)

Technology *variables*	**Description of the variable**	**mean**	**SD**
Adopt_Ferti	If the farmer used chemical fertilizer in the 2006 E.C Maher season (1=yes, 0=no)	0.53	0.49
Dis_Fertilizer	If the farmer stopped using chemical fertilizer (1=yes, 0=no)	0.32	0.47
Adopt_Imvseed	If the farmer used improved seed in the Maher 2006 E.C season (1=yes, 0=no)	0.38	0.48
Dis_Seed	If the farmer stopped using improved seed (1=yes, 0=no)	0.18	0.38
Adopt_manure	If the farmer used manure in the Maher 2006 E.C season or before (1=yes, 0=no)	0.25	0.43
Adopt_soil cons	If the farmer has used soil conservation methods on the plot((1=yes, 0=no)	0.51	0.50
Plot characteristics	**Description of the variable**	**mean**	**Std. Dev**
walka_soil	If the soil type/color is black /brown (1=yes, 0=no)	0.25	0.43
Keyehtay	If the soil type is reddish (1=yes, 0=no)	0.47	0.49
Sheshher	If the soil type/color is sandy (grey color) (1=yes, 0=no)	0.28	0.45
Experience_ fertilizer	Number of years using inorganic fertilizer before stopping using it on the plot	5.0	3.2
Experience_ seed	Number of years using improved seed before stopping using it on the plot	3.5	4.2
Owner_type	If the plot is owned or rented in (1=owned, 0= rented in)	0.84	0.36
plottslope	Slope of the plot as perceived by the farmer on a 4-point scale where 1 means flat and 4 means very sloping	1.45	0.73
Irrigation	If the farmer uses irrigation on this plot (1=yes, 0=no)	0.18	0.38
lndistancetohome	Distance from the homestead to the plot (in minutes and log form)	2.3	1.35
Socio-economic characteristics	**Description of the variable**	**mean**	**Std. Dev**
gender	Gender of the household head	0.89	0.30
age	Age of the household head	46.5	13.00
educationlevel	Education of the household head (in years of schooling)	1.5	2.10
Risk_pref	Subjective risk preference on a 5-point scale, where 0 means most risk averse and 4 means least risk averse	0.81	0.99
Time-pref	Subjective time preference on a 5-point scale, where 0 means most patient and 4 means least patient	2.5	1.24
hhsizze	Household size	5.4	1.94
lnwealth	Value of assets in 1000 ETB (in log)	3.0	1.16
Off-farm work	If the farmer participates in off-farm income generating activities (1=yes, 0=no)	0.54	0.50
Livestock_TLU	Number of livestock in Tropical Livestock Units (TLU)	4.13	2.98
lndistance_extcenter	Distance from the homestead to the extension center (in minutes and log form)	3.27	1.92
lndistance_market	Distance from the homestead to the nearest market (in minutes and log form)	3.78	0.64
Observations		1,344	

Table 2: Reasons for disadoption of inorganic fertilizer and improved seed

Reason for disadoption of inorganic fertilizer	percent	Reason for disadoption of improved seed	percent
1.Increase in price and I can't afford to buy it anymore	12.79%	1.Increase in price and I can't afford to buy it anymore	18.62%
2.I do not get much difference in yield and income in good rains and hence I do not need to use it again	6.51%	2.I do not get much difference in yield and income in good rains and hence I do not need to use it again	31.58%
3.It is not available in a nearby market	2.56%	3.The type I need is not available in a nearby market	17.81%
4.Risk of low yield because previous trial was not successful due to crop burn/low yield with low amount of rainfall	75.12%	4.Risk of low yield because previous trial was not successful due to low amount of rainfall	22.27%
5.Other	3.02%	5.Other	9.72%

*Table 3 The conditional and unconditional probabilities in **Adoption decision***

	Fertilizer	Seed	manure	Soil conserv.
P(y=1)	53%	38%	25%	51%
P(y=1/fertilizer=1)	100%	48%	16%	44%
P(y=1/seed=1)	66%	100%	40%	79%
P(y=1/manure=1)	35%	61%	100%	81%
P(y=1/soil consv=1)	46%	59%	40%	100%
P(y=1/soil consv=1, manure=1)	23%	55%	100%	100%
P(y=1/improved seed=1, manure=1)	35%	100%	100%	74%
P(y=1/fertilizer=1, manure=1)	100%	62%	100%	20%
P(y=1/fertilizer=1, improved seed=1)	100%	100%	21%	68%
P(y=1/fertilizer=1, soil=1)	100%	73%	20%	100%
P(y=1/improved seed=1, soil=1)	57%	100%	37%	100%
P(y=1/improved seed=1, manure=1 and soil=1)	12%	100%	100%	100%
P(y=1/fertilizer=1, manure=1 and soil=1)	100%	29%	100%	100%
P(y=1/fertilizer=1, improved seed=1 and soil=1)	100%	100%	8%	100%
P(y=1/fertilizer=1, improved seed=1 and manure=1)	100%	100%	100%	25%

Where y= {chemical fertilizer, improved seed, manure and soil conservation methods}

*Table 4 The conditional and unconditional probabilities in **Disadoption and non-adoption decisions***

	Disadopt fertilizer	Disadopt improved seed	Non-adopt manure	Non-adopt-Soil
P(y=1)	32%	18%	75%	49%
P(y=1/Dis Adopt_fertilizer=1)	100%	37%	98%	60%
P(y=1/Dis Adopt_Seed=1)	65%	100%	88%	58%
P(y=1/manure_NA=1)	42%	22%	100%	59%
P(y=1/manure=1)	2%	9%	-	-
P(y=1/Soil_NA=1)	39%	22%	90%	100%
P(y=1/Soil=1)	25%	15%	-	-
P(y=1/Dis Adopt_fertilizer=1,Dis Adopt_Seed=1)	100%	100%	64%	46%
P(y=1/Dis Adopt_fertilizer=1,manure_NA=1)	100%	37%	100%	60%
P(y=1/Dis Adopt_Improvedseed=1,manure_NA=1)	72%	100%	100%	65%
P(y=1/Siol_NA=1,manure_NA=1)	43%	24%	100%	100%
P(y=1/Dis adopt_Fertilizer=1 Soil_NA=1)	100%	44%	99%	100%
P(y=1/Dis adopt_Seed=1 Manure_NA=1)	72%	100%	100%	65%

Where y= {disadoption of chemical fertilizer, disadoption of improved seed, adoption of manure (manure), non-adoption of manure (manure_NA), adoption of soil conservation methods (Soil) and non-adoption of soil conservation methods (Soil_NA)} and NA=non-adoption

Table 5: Random effect Probit Multivariate Regression Results of Adoption and Disadoption of Agricultural Practices

	Adopt Inorganic Fertilizer		Disadopt Inorganic Fertilizer		adopt Improved seed		Disadopt Improved seed		Adopt Manure		Adopt Soil. Conserv.	
VARIABLES	Coef	R.SE	Coef	R.SE	Coef	R.SE	Coef	R.SE	Coef	R.SE	Coef	R.SE
Walka soil	0.97***	0.15	-1.11***	0.18	0.22	0.16	-0.51**	0.23	0.21	0.15	-0.30**	0.14
Plot slope	-0.65***	0.09	0.52***	0.10	-0.43***	0.11	0.69***	0.14	-0.29**	0.11	0.20**	0.09
Use irrigation	0.50***	0.17	-0.76***	0.22	0.62***	0.17	-0.28	0.30	0.25	0.19	0.36**	0.17
Land ownership type	0.48***	0.16	-0.55***	0.19	0.32	0.20	-0.55**	0.23	0.14	0.21	-0.06	0.17
Plot size	0.02	0.06	-0.04	0.06	0.00	0.07	0.09	0.06	-0.01	0.06	0.02	0.06
Plot distance	-0.04	0.05	0.13**	0.06	-0.35***	0.05	0.54***	0.08	-0.21***	0.06	-0.22***	0.05
Number of years the modern technology applied in the plot			-0.07***	0.02	-0.24***	0.03						
Risk preference	0.20***	0.04	-0.13***	0.05	0.05	0.04	-0.20***	0.07	-0.16***	0.04	-0.01	0.04
Time preference	-0.10***	0.04	-0.01	0.04	-0.39***	0.05	-0.17***	0.06	-0.14***	0.04	-0.29***	0.04
Gender	0.12	0.13	-0.08	0.15	0.18	0.17	0.53***	0.19	0.14	0.15	0.18	0.14
Wealth (log)	0.13***	0.03	-0.11***	0.04	0.07*	0.04	0.03	0.06	0.02	0.04	0.06*	0.03
Participation in off-farm Income	0.51***	0.08	-0.17*	0.09	0.06	0.09	0.03	0.12	-0.10	0.09	-0.09	0.08
Education level	0.04*	0.02	-0.04*	0.02	0.12***	0.02	-0.11***	0.03	0.02	0.02	0.03	0.02
Household size	0.01	0.02	-0.07***	0.02	0.13***	0.02	-0.15***	0.03	0.09***	0.02	0.11***	0.02
Age of the household head	0.00	0.00	0.00	0.00	0.00	0.00	0.01**	0.01	-0.00	0.00	0.00	0.00
Distance to extension center	-0.00	0.04	0.09**	0.04	-0.19***	0.05	0.10*	0.05	-0.16***	0.04	-0.15***	0.04
Distance to market	-0.01	0.07	-0.00	0.08	0.01	0.07	-0.00	0.12	0.01	0.08	0.20***	0.07
Number of livestock (in TLU)									0.49***	0.12		
Village dummies	Yes		Yes		Yes		Yes		Yes		Yes	
Constant	-0.78**	0.39	0.60	0.46	0.67	0.47	-3.69***	0.73	-1.11**	0.51	-0.57	0.42
correlations of error terms	Coef.	R.SE	corr.	Coef.	R.SE	corr.	Coef.	R.SE				
$\rho_{F^d F^a}$	-0.74***	0.041	$\rho_{V^a F^d}$	-0.41***	0.049	$\rho_{M^a V^a}$	0.34***	0.049				
$\rho_{V^a F^a}$	0.20***	0.058	$\rho_{V^d F^d}$	0.14*	0.075	$\rho_{S^a V^a}$	0.56***	0.042				
$\rho_{V^d F^a}$	-0.10	0.070	$\rho_{M^a F^d}$	-0.20***	0.06	$\rho_{M^a V^d}$	-0.18***	0.050				
$\rho_{M^a F^a}$	-0.40***	0.051	$\rho_{S^a F^d}$	-0.12**	0.058	$\rho_{S^a V^d}$	-0.21***	0.061				
$\rho_{S^a F^a}$	-0.25***	0.054	$\rho_{V^d V^a}$	-0.36***	0.083	$\rho_{M^a S^a}$	0.53***	0.04				
Joint significance of correlation of unobservables in all equations [likelihood ratio test]: $\chi^2(15) =$ 952.734 Prob > χ^2 = 0.0000												
Joint significance of mean of plot-varying variables in the model: $\chi^2(36) =$ 60.72, Prob > chi2 = 0.006												
Wald $\chi^2(195)$ = 1987.51, Prob > χ^2 = 0.0000												
Observations	1,344		1,344		1,344		1,344		1,344		1,344	1,344

Note:*, **, *** indicate statistical significance at 10, 5 and 1%, respectively. R.SE is robust standard error

Table 6: A Random Effects Linear Multivariate Regression Results of Adoption and Disadoption of Agricultural Practices

	Adopt Inorganic Fertilizer		Disadopt Inorganic Fertilizer		adopt Improved seed		Disadopt Improved seed		Adopt Manure		Adopt Soil. Conserv.	
VARIABLES	Coef	B.SE	Coef	B.SE	Coef	B.SE	Coef	B.SE	Coef	B.SE	Coef	B.SE
Walka soil	0.28***	0.04	-0.20***	0.04	0.04	0.04	-0.06**	0.03	0.04	0.04	-0.09*	0.05
Plot slope	-0.22***	0.03	0.18***	0.03	-0.08***	0.03	0.13***	0.02	-0.05*	0.03	0.08***	0.03
Use irrigation	0.14***	0.05	-0.15***	0.04	0.18***	0.05	-0.03	0.03	0.08	0.06	0.12**	0.05
Land ownership type	0.12**	0.05	-0.16***	0.05	0.05	0.05	-0.12***	0.04	0.06	0.05	0.02	0.06
Plot size	0.00	0.02	-0.00	0.02	-0.00	0.02	0.02	0.01	-0.01	0.02	-0.00	0.02
Plot distance	-0.01	0.01	0.02*	0.01	-0.09***	0.01	0.08***	0.01	-0.06***	0.01	-0.08***	0.02
Number of years the modern technology applied in the plot			-0.00*	0.00	-0.02***	0.00						
Risk Preference	-0.04***	0.01	-0.04***	0.01	0.00	0.01	-0.02**	0.01				
Time preference	0.03***	0.01	-0.00	0.01	-0.11***	0.01	-0.04***	0.01	-0.03***	0.01	-0.10***	0.01
Gender	0.03	0.04	-0.03	0.04	0.05	0.04	0.06**	0.03	0.05	0.04	0.06	0.04
Wealth (log)	0.03***	0.01	-0.03***	0.01	0.01	0.01	0.00	0.01	0.00	0.01	0.03**	0.01
Participation in off-farm income	0.15***	0.03	-0.03	0.02	0.01	0.02	0.01	0.02	-0.04	0.02	-0.02	0.03
Education level	0.01*	0.01	-0.01**	0.01	0.03***	0.01	-0.02***	0.00	0.01	0.01	0.01*	0.01
Household size	0.00	0.01	-0.02***	0.01	0.03***	0.01	-0.02***	0.00	0.02***	0.01	0.04***	0.01
Age of the household head	0.00	0.00	0.00	0.00	-0.00	0.00	0.00**	0.00	-0.00*	0.00	0.00	0.00
Distance to extension center	-0.00	0.01	0.02**	0.01	-0.04***	0.01	0.01	0.01	-0.05***	0.01	-0.05***	0.01
Distance to market	-0.00	0.02	0.01	0.02	0.01	0.02	0.00	0.02	0.01	0.02	0.06***	0.02
Number of livestock (in TLU)									0.05**	0.02		
Village dummies	Yes		Yes		Yes		Yes		Yes		Yes	
Constant	0.33**	0.14	0.42***	0.13	0.74***	0.12	-0.06	0.09	0.21*	0.12	0.31**	0.14
correlations of error terms	Coef.	corr.	Coef.	corr.	Coef.							
$\rho_{F^dF^a}$	-0.58	$\rho_{V^aF^d}$	-0.22	$\rho_{M^aV^a}$	0.14							
$\rho_{V^aF^a}$	0.24	$\rho_{V^dF^d}$	0.18	$\rho_{S^aV^a}$	0.33							
$\rho_{V^dF^a}$	-0.11	$\rho_{M^aF^d}$	-0.34	$\rho_{M^aV^d}$	-0.22							
$\rho_{M^aF^a}$	-0.34	$\rho_{S^aF^d}$	-0.16	$\rho_{S^aV^d}$	-0.23							
$\rho_{S^aF^a}$	-0.18	$\rho_{V^dV^a}$	-0.11	$\rho_{M^aS^a}$	0.29							
Joint significance of correlation of unobservables in all equations [likelihood ratio test]: $\chi^2(15) =$ 1217.102, Prob > χ^2 = 0.000												
Joint significance of mean of plot-varying variables in the model: $\chi^2(36) =$ 75.13 Prob > chi2 = 0.000												
Joint significance of all explanatory variables in the model $\chi^2(122)$ 7479.38, Prob > χ^2 = 0.000												
Observations	1,344		1,344		1,344		1,344		1,344		1,344	
R-squared	0.30		0.34		0.41		0.48		0.17		0.23	

Note:*, **, *** indicate statistical significance at 10, 5 and 1%, respectively. B.SE is bootstrap standard error

Table 7: Fixed effect Linear Multivariate Regression Results of Adoption and Disadoption of Agricultural Practices

	Adopt Inorganic Fertilizer		Disadopt Inorganic Fertilizer		adopt Improved seed		Disadopt Improved seed		Adopt Manure		Adopt Soil. Conserv.	
VARIABLES	Coef	B.SE	Coef	B.SE	Coef	B.SE	Coef	B.SE	Coef	B.SE	Coef	B.SE
Walka soil	0.30***	0.03	-0.22***	0.03	0.05*	0.03	-0.10***	0.02	0.06*	0.03	-0.09**	0.04
Plot slope	-0.05***	0.01	0.02**	0.01	-0.01	0.01	0.04***	0.01	-0.02***	0.01	0.05***	0.01
Use irrigation	0.17***	0.04	-0.17***	0.03	0.20***	0.04	-0.08***	0.02	0.09*	0.04	0.11**	0.05
Land ownership type	0.17***	0.04	-0.21***	0.04	0.08**	0.03	-0.15***	0.03	0.07**	0.03	0.01	0.04
Plot size	0.01	0.01	-0.00	0.01	-0.00	0.01	0.02**	0.01	-0.01	0.01	-0.00	0.01
Plot distance	-0.00	0.01	0.03***	0.01	-0.10***	0.01	0.10***	0.01	-0.06***	0.01	-0.08***	0.01
Number of years the modern technology applied in the plot			-0.01***	0.00			-0.01***	0.00				
Constant	-0.00	0.01	-0.00	0.01	-0.00	0.01	-0.00	0.00	-0.00	0.01	-0.00	0.01
Correlations of error terms	Coef.	corr.	Coef.	corr.	Coef.							
$\rho_{F^d F^a}$	-0.58	$\rho_{V^a F^d}$	-0.31	$\rho_{M^a V^a}$	0.25							
$\rho_{V^a F^a}$	0.36	$\rho_{V^d F^d}$	0.22	$\rho_{S^a V^a}$	0.30							
$\rho_{V^d F^a}$	-0.21	$\rho_{M^a F^d}$	-0.45	$\rho_{M^a V^d}$	-0.21							
$\rho_{M^a F^a}$	-0.30	$\rho_{S^a F^d}$	-0.13	$\rho_{S^a V^d}$	-0.25							
$\rho_{S^a F^a}$	-0.22	$\rho_{V^d V^a}$	-0.27	$\rho_{M^a S^a}$	0.28							
Joint significance of correlation of unobservables in all equations[likelihood ratio test]: $\chi^2(15)$ = 1494.831, Prob > χ^2 = 0.0000												
Joint significance of all explanatory variables in the model $\chi^2(36)$ = 647.66, Prob > χ^2 = 0.0000												
Observations	1,344		1,344		1,344		1,344		1,344		1,344	
R-squared	0.17		0.17		0.15		0.26		0.07		0.08	

Note:*, **, *** indicate statistical significance at 10, 5 and 1%, respectively. B.SE is bootstrap standard error

Appendix B

Risk and Time Preference Questions

B1.Risk preference

In what follows, we ask you to make a decision based on a hypothetical game of random chance by flipping a 5 cent coin (Ethiopian currency). As you know, the 5 cent coin has two sides, identified as 'lion head'and 'man'(Enumerator: Use the coin to explain). If we flip the coin, either the 'lion head side'or 'man side'will appear with equal chance and a monetary amount is attached to either outcome (Enumerator: Flip the coin as a practice to explain equal chance).

A1.1. Before we continue, we would like to ask you your understanding of a random chance. If we flip the coin, which side will appear? (Enumerator: After writing down the answer, explain the correct answer.)

A. Lion head

B. Man

C. One of them will appear with equal chance

D. I do not know

A1.2. Now we are going to flip the coin. Before that, which one of the monetary values associated with one of the outcomes of the flipping coin do you choose?

A. 250 Birr regardless of whether it is lion or man

B. 200 Birr if it is lion, 400 Birr if it is man

C. 150 Birr if it is lion, 550 Birr if it is man

D. 100 Birr if it is lion, 700 Birr if it is man

E. 0 Birr if it is lion, 1000 Birr if it is man

B2.Time preference

Imagine now that you have won a lottery and that the prize can be paid at different points in time: today or after one year. *What amount of money would you prefer in each choice situation A-D?*

A. 5,000 ETB today or 5,500 ETB after one year, amount chosen―――――

B. 5,000 ETB today or 7,000 ETB after one year, amount chosen―――――

C. 5,000 ETB today or 9,000 ETB after one year, amount chosen―――――

D. 5,000 ETB today or 11,000 ETB after one year, amount chosen―――――

Paper III

Household fuel choice in urban China: Evidence from panel data*rr

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Abstract

Using seven rounds of household survey data that span more than a decade, this paper analyzes the determinants of household fuel choice in urban China. Using a correlated random effects generalized ordered probit model, we find that household fuel choice in urban China is related to fuel prices, household's economic status and size, and household head's gender and education. Our results suggest that policies and interventions that reduce prices of clean fuel sources and empower women in the household are of great significance in encouraging the use of clean energy sources.

JEL classification: C25, Q23, Q40, Q42

Key words: Household fuel choice; Panel data; Random effects generalized probit model; Urban China

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1. Introduction

Half of the world's population and up to 95% of people in developing countries rely on solid fuels (biomass fuels and coal) to meet their energy needs (International Energy Agency [IEA], 2010). Household dependence on solid fuels for cooking has health and environmental impacts. Conservative estimates document that exposure to indoor smoke produced by household solid fuel combustion is responsible for about 2 million premature deaths per year globally, which is 3.3% of the global burden of disease. About 550,000 of these deaths occurred in China alone in 2004 (Smith et al., 2004; World Health Organization, 2008).

With increasing household well-being and income in China, especially in the urban areas, our data shows that more and more households have shifted from the traditional firewood or coal to modern energy, such as liquefied natural gas (LNG) or electricity. China's experience makes it a good example to investigate the economic and social determinants of the transition in choices of household cooking fuels. Understanding these determinants will be helpful in order to find ways to accelerate the transition to cleaner fuels in other developing countries as well.

Traditionally, the "energy ladder" hypothesis has been used to explain households' fuel choices and switching behavior in developing countries. This hypothesis describes income as the sole factor in determining these decisions. However, fuel choice behavior of households is not as simple as prescribed by the traditional energy ladder hypothesis (Masera et al., 2000; Heltberg, 2005). The simple association between income and fuel demand (choice) has been criticized because fuel choice can be affected by a multitude of demographic and socio-economic factors (Masera et al., 2000; Heltberg, 2005; Mekonnen and Köhlin 2008).

A number of studies have analyzed the determinants of household fuel choice in the developing world. However, many of these studies are based on cross-sectional data (e.g., Hosier and Dowd, 1987; Leach, 1992; Farsi et al., 2007) and studies employing panel data are rare (e.g.Mekonnen and Köhlin, 2008). Moreover, previous studies in China are mainly based on aggregate statistics or on surveys conducted in a certain province or counties (e.g., Energy Sector Management Assistance Programme [ESMAP], 1996; Wang and Feng, 1997; Chen et al., 2006). To the best of our knowledge, very few studies have examined household energy choices in China through longitudinal data from a nationwide household survey. This paper tries to fill this gap by using seven rounds of panel data from the China Health and Nutrition Survey (CHNS). The panel data enable us to control for unobserved household heterogeneity and time trends in the analysis of household fuel choice.

The paper's focus is on households' primary cooking fuel choices in urban areas of China. The reason for this is the fact that fuel choices of rural households are largely determined by fuel availability and opportunity costs for fuel collection rather than by budget constraints, which complicates the modeling of household fuel choice in such circumstances (Farsi et al., 2007). Moreover, while fuel choices for cooking and heating are the main interests of the literature on household energy choices, this paper is able to focus on cooking fuel choice because heating in urban China is mainly provided at the district level, which means that households have little freedom to choose the type of heating energy used. Finally, we focus on households' choices of primary cooking energy. Primary cooking energy is the type that is most frequently used by a household.[1] Farsi et al. (2007) used a similar definition in their study of fuel choice in India.

In line with Farsi et al. (2007), ordered probit models were employed to take into account the potential ordering of different fuels in terms of efficiency or convenience to use. In addition, we contribute two extensions to the application of an ordered discrete choice model to the fuel choice issue. First, this paper employs a more flexible empirical framework

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[1]The survey identifies the cooking fuel used most frequently by a household. Due to lack of information on the proportion of each fuel for households that use multiple fuels, it is difficult to effectively incorporate multiple fuel choices into our analysis.

through generalized ordered probit models rather than the standard ordered probit model. The standard model is based on a restrictive assumption of the parallel regression or the same slope coefficients across the different fuel categories, implying a homogenous effect of the explanatory variables across the distribution of fuel categories. Second, to explore the panel structure of the data set, a random effect generalized ordered probit model with Mundlak transformation is adopted to analyze household fuel choices. The Mundlak approach enables us to address the potential bias that would come from possible correlation between the unobserved heterogeneity and the explanatory variables.

Our results suggest that policies and interventions that raise households' income, reduce prices of clean fuel sources, and empower women in the household are of great significance in encouraging the adoption of clean energy sources. The results also show the importance of other socio-demographic factors such as education in determining the choice of primary cooking fuels in urban Chinese households.

This paper is organized as follows. Section 2 provides a brief review of the related literature. Section 3 describes the empirical strategy used in this study. Section 4 presents the data and some descriptive statistics. The estimation results of our econometric model are illustrated and discussed in Section 5. Finally, section 6 summarizes the conclusions and policy implications.

2. Review of Literature

A growing body of empirical literature tries to investigate energy choices and switching strategies of households in developing countries. These studies focus on the effect of household characteristics, income and prices on fuel choices and also on the validity of the energy ladder hypothesis. Lewis and Pattanayak (2012) undertake a meta-analysis on the question of who adopts improved fuels and cookstoves in developing countries and document that the literature remains scattered and largely qualitative. In the paragraphs below, we present a brief review of previous studies, focusing on households' fuel choices and switching behavior, and highlighting existing knowledge gaps.

The energy ladder hypothesis is based on the assumption that households are exposed to a number of fuel choices, which can be ranked in order of increasing efficiency and technological sophistication, and that households make the transition to the higher-ranked fuel as their income rises (Hosier and Dowd, 1987). Electricity, natural gas and other commercial fossil fuels are ranked higher than the traditional biomass fuels. The energy choice of a household will move "up" the energy ladder to higher-ranked fuels as its income increases. A few earlier studies provide evidence for this hypothesis (e.g., Alam et al., 1985; Sathaye and Tyler, 1991). Alam et al. (1985) found that income has a direct effect on household fuel choice decisions. The higher the income level, the greater the tendency for households to choose commercial fuels over biomass fuels. Using a cross-section of 1,000 sample households from Bangalore, India, Reddy (1995) examined household energy choices through a series of binomial logit models for different pairs of energy carriers. This author confirmed the hypothesis of the energy ladder and the importance of income in household energy choices.

However, Reddy (1995, p. 936) also argued that "as times change, societies become more egalitarian and this energy-ladder concept based on income may disappear." In fact, the simple association between income and fuel choice has been criticized in more recent literature. Fuel choice can be affected by a multitude of demographic and socio-economic factors (Davis, 1998; Masera et al., 2000; Barnett, 2000; Heltberg, 2005; Mekonnen and Köhlin, 2008). A limited but increasing number of studies from the largest developing countries, such as India and China, provide evidence on the multiple factors that determine household fuel choice (e.g., Jiang and O'Neill, 2004; Farsi et al., 2007; Pachauri and Jiang, 2008). Further, a review study on energy, gender and development by Köhlin et al. (2011) documented that the energy ladder hypothesis is challenged by recent studies and concluded that households in developing countries are characterized by "fuel stacking", i.e., adding cleaner energy sources without entirely abandoning traditional fuel sources. From the above studies, in addition to household income, household size, fuel price, and education and gender of the household head are found to be among the key determinants of fuel choice and transition.

Despite these findings, the existing empirical research in this area documents mixed results for some of these factors. For example, while Hosier and Dowd (1987) found that large households tend to move away from wood and toward kerosene, the findings of Ouedraogo (2006) indicate that small households are more likely to use LPG and less likely to use firewood. Unlike these two studies, Heltberg (2004) found insignificant effects of household size on fuel transition (switching). Similarly, the empirical evidence on the effect of prices or relative prices is also mixed. Leach (1992) found that relative fuel prices are less important for households' substitution of traditional biomass fuels by modern energy sources. Likewise, Zhang and Kotani (2012) found that coal and LPG prices do not exhibit substitution effects. Nonetheless, Heltberg (2005), Gundimeda and Köhlin (2006) and Gupta and Köhlin (2006) found significant cross-price effects between different fuel types. Lewis and Pattanayak (2012), in all the studies they reviewed, found that the effect of fuel price is unclear. Further, Köhlin et al. (2011), in their review, documented that only a few studies estimate the cross-price elasticity of fuel demand and suggest more studies with more fuel sources and larger sample size.

Regarding the effect of education, most studies found positive effects of education on the transition to high quality fuel (e.g., Heltberg, 2004; Jiang and O'Neill, 2004; Heltberg, 2005; Farsi et al., 2007). Some studies also looked at the effect of locations or regions where households reside. This captures the difference in access to the fuel sources (Hosier and Dowd, 1987; Leach, 1992; Heltberg, 2004; Heltberg, 2005). Contrary to the energy ladder hypothesis, recent literature documents that "fuel switching" in developing countries is often a gradual process, with many households using multiple fuels; the reasons for multiple fuel use (fuel stacking) are varied, from supply security to cultural, social or taste preferences (Masera et al., 2000; Heltberg, 2005; Farsi et al., 2007; Mekonnen and Köhlin, 2008).

Many studies have analyzed the determinants of fuel choices in the developing world based on cross-sectional data (e.g., Hosier and Dowd, 1987; Leach, 1992; Farsi et al., 2007). Few studies have employed panel data (e.g., Mekonnen and Köhlin 2008, Alem et al. ,2013). Regarding the studies on China, most of them are based on aggregate statistics, on surveys conducted in certain provinces or counties, or on rural households (ESMAP, 1996; Wang and Feng, 1997; Chen et al., 2006; Peng et al., 2010; Zhang and Kotani, 2012). Based on aggregate statistics and descriptive statistical tests, Cai and Jiang (2007) tested the energy ladder hypothesis by comparing the energy consumption pattern of rural households with that of urban households. Their results show that urban households use fuel that is more convenient, cleaner, and more efficient than fuels used in rural areas, where biomass and coal commonly dominate. Peng et al. (2010) studied household-level fuel switching using cross-sectional data from rural Hubei. They found that fuel use varies enormously across geographic regions due to disparities in availability of different energy sources. Their results indicate that rural households do switch to commercial energy sources, with coal as the principal substitute for biomass. Using a household survey from rural Beijing, Zhang and Kotani (2012) found that coal and liquefied petroleum gas (LPG) prices do not exhibit substitution effects. Jiang and O'Neill (2004) explored patterns of residential energy use in rural China by using a nationally representative rural household survey and various sources of aggregate statistics.

From the above empirical evidence on fuel choices in China and other developing countries, we observe the following knowledge gaps. First, many of the existing studies in China are based on surveys in a certain province or county. Due to the large regional variations across China, the experience from one region may not be perfectly applicable in another region, which highlights the importance of controlling regional variations in relevant studies. Second, most of the previous studies on household fuel choice in developing countries are based on cross-sectional data in which it is difficult to control for unobserved household heterogeneity and the potential bias from the correlation of unobserved heterogeneity and explanatory variables. Our study seeks to fill these gaps.

3. Empirical Strategy

Our choice of empirical strategy is based on the ordinal ranking of different fuel types in terms of their cleanliness, convenience to use, and modernity (see Figure A1 in the Appendix), which is also consistent with the transition of households in urban China from solid fuel sources to clean energy over the past couple of decades, as discussed in the section below. For instance, among the three fuel types considered in this study (firewood, coal and LNG), LNG is the most efficient and convenient to use, while firewood is the least efficient and least convenient to use. Considering this, an ordered discrete choice framework is used in this study. However, one may argue that the real process of decision-making is not known to econometricians; hence, the ranking of the fuels may not be obvious. Alternatively, one may use a multinomial logit model rather than an ordered regression model. Nonetheless, Anderson (1984) argued that, in cases where ordering is not "*a priori* obvious," a generalized ordered probit/logit model (which will be discussed later in this section) is preferable for the interpretation of coefficient estimates. Also, a multinomial logit model will result in inefficient estimates if the ordering is inherent in the household fuel preference (Boes and Winkelmann, 2010). Ordered probit models already have been applied to household cooking fuel choices in the recent literature (e.g., Farsi et al., 2007; Mensah and Adu 2013; Nlom and Karimov, 2014). However, to our knowledge, none of the studies using ordered probit models have analyzed household fuel choice by employing the ordered probit model with panel data application, where the unobserved individual heterogeneity can be better dealt with by exploring the panel structure of the data set.

Given the above ordinal fuel choice structure and assuming that individual households' fuel choices are based on a latent variable (E_{it}^*), the random effect ordered response model can be written as:

$$E_{it}^* = x_{\mathrm{it}}'\beta + \alpha_i + \varepsilon_{it},\ (\varepsilon_{it} \big| x_{it}) \sim N(0,1)\ ,\ (\alpha_i \big| x_{it}) \sim N(0,\sigma_\alpha^2) \tag{1}$$

$$E_{it} = j \text{ if } \mu_{j-1} < E_{it}^* < \mu_j \ \text{ for } j = 0,1,2,\ldots J \text{ and } \mu_{-1} = -\infty,\ \mu_J = +\infty \tag{2}$$

where E_{it} represents the observed cooking fuel choice for household $i = 1,...,n$ in time period $t = 1,...T$, which can be ordered in terms of efficiency or convenience (e.g., $E=0$ for firewood, $E=1$ for coal, and $E=2$ for LNG, etc.). x_{it} denotes a vector of explanatory variables, including income and other household characteristics. β is the vector of parameter estimates for explanatory variables, and μ denotes the unknown threshold values to be estimated with β . ε_{it} is the time-varying unobserved heterogeneity, which is assumed to be normally distributed with mean zero and variance one. α_i is the time-invariant unobserved heterogeneity. Conditional on x_{it} , α_i is normally distributed with mean zero and variance σ_α^2 , and is assumed to be independent of ε_{it} and x_{it} ; this assumption will be relaxed later on. Under these assumptions, it can be shown that the correlation between the composite error terms ($\alpha_i + \varepsilon_{it}$) across any two time periods is given by $\rho = \dfrac{\sigma_\alpha^2}{\sigma_\alpha^2 + \sigma_\varepsilon^2}$, which can also be considered as a measure of the relative importance of the unobserved effect (Wooldridge, 2010, pp.608-662). Conditional on x_{it} and α_i , the random effect ordered probit model is:

$$P(E_{it} = j \mid x_{it}, \alpha_i) = \Phi(\mu_j - \alpha_i - x_{\mathrm{it}}'\beta_j) - \Phi(\mu_{j-1} - \alpha_i - x_{\mathrm{it}}'\beta_j) \text{ for } j = 0,1,2,\ldots J \tag{3}$$

where Φ is the standard normal cumulative distribution function with $\Phi(\mu_{-1}) = 0$ and $\Phi(\mu_J) = 1$. From equation (3), we can see that the random effect ordered probit model takes into account the unobserved heterogeneity, which cannot be handled in the standard ordered probit analysis using cross-sectional data.

However, the standard random effect ordered probit models implicitly impose the parallel regression assumption. This implies homogenous effect of the explanatory variables across the cumulative distribution of cooking fuel types, i.e., single crossing of marginal probability effects or constant relative effects (Maddala, 1983; Boes and Winkelmann, 2005). To relax this rather restrictive assumption, we can employ a more flexible framework through a generalized ordered probit model, where the effects of explanatory variables across the cumulative distribution of the dependent variable are unrestricted (Boes and Winkelmann, 2005). This can be carried out by making the threshold values linear functions of the explanatory variables, i.e., $\mu_{ij} = k_j + x'_{\mathrm{it}}\lambda_j$ (Terza, 1985). Substituting $\mu_{ij} = k_j + x'_{\mathrm{it}}\lambda_j$ in Eq. (3) gives the generalized random effect model:

$$P(E_{it} = j \mid x_{it}, \alpha_i) = \Phi(k_j - \alpha_i - x'_{\mathrm{it}}\beta_j) - \Phi(k_{j-1} - \alpha_i - x'_{\mathrm{it}}\beta_j),\ j = 0,1,2,\ldots J \qquad (4)$$

where the estimated coefficients are $\beta_j = \beta - \lambda_j$. Thus, we can see that the heterogeneity in the generalized model causes the vector of parameter estimates, β_j, to become category-specific. The standard random effect ordered probit model can be considered as a special case of the generalized model with the imposition of the restriction $\beta_1 = \ldots = \beta_J$.

Both the standard and general random effects ordered probit models assume that time-invariant unobserved heterogeneity (α_i) is independent of the explanatory variables. However, this is a rather restrictive assumption, as some of the time-invariant unobserved heterogeneity, such as motivation, may be correlated with some of the regressors in the model, such as education and income, which in turn may introduce bias in the coefficient estimates. Following Boes and Winkelmann (2010), Chamberlain (1980), and Mundlak (1978), it is possible to estimate more precise estimates for the generalized ordered probit framework by allowing for possible correlation between α_i and x_{it}, which involves including the averages of time-varying regressors in the model.[2] This approach relies on the assumption that the time-invariant unobserved effects are linearly correlated with explanatory variables, as specified by:

$$\alpha_i = \bar{x}_i\gamma + \upsilon_i \tag{5}$$

where $\bar{x}_i$ is the vector of the averages of x_{it} over time, γ is parameter vector and υ_i is an orthogonal error with $\upsilon_i|\bar{x}_i \sim \mathrm{N}(0,\sigma_\upsilon^2)$. Replacing α_i in equation (4) with equation (5), we obtain:

$$P(E_{it} = j \mid x_{it}, \bar{x}_i, \upsilon_i; \gamma, \beta) = \Phi(k_j - \upsilon_i - x'_{it}\beta_j - \bar{x}'_i\gamma) - \Phi(k_{j-1} - \upsilon_i - x'_{it}\beta_{j-1} - \bar{x}'_i\gamma) \text{ for } j = 0,1,2,...J \tag{6}$$

The resulting modification (6) is the so-called "correlated random-effects generalized ordered probit model" or "random-effects generalized ordered probit with Mundlak transformation." The two names are used interchangeably hereinafter. The joint distribution of $E_i = (E_{i1},..., E_{iT})$ can then be obtained by integrating equation (6) over υ_i, formally:

$$f(E_i \mid x_{it}, \bar{x}_i; \gamma, \beta, \sigma_\upsilon^2) = \int_{-\infty}^{\infty} \prod_{t=1}^{T_i} \prod_{j=0}^{J} P(E_{it} = j \mid x_{it}, \bar{x}_i, \upsilon_i; \gamma, \beta)^{1(E_{it}=j)} \frac{1}{\sigma_\upsilon} \phi(\frac{\upsilon_i}{\sigma_\upsilon}) d\upsilon_i \tag{7}$$

[2] The application of the standard fixed effects method to generalized discrete choice models, however, is not easy, as there is no simple transformation (first difference or within transformation). This is also difficult for standard ordered probit due to its functional form complexity. As a result, the application of a fixed effects method to ordered probit models is rare. Nonetheless, the application of a standard fixed effects method is relatively easier for ordered logit models and there are a growing number of empirical studies based on fixed effects ordered logit models (e.g. Booth and van Ours, 2008; Kassenboehmer and Haisken-DeNew, 2009). In the appendix of this version, we also present the results from two fixed effects estimates of ordered logit models that are commonly used in the literature: the Ferrer-i-Carbonell and Frijters (FF) estimator (Ferrer-i-Carbonell and Frijters, 2004) and the "Blow-up and Cluster" (BUC) estimator (Baestschmann et al., 2011; Dickerson et al. 2012) (which is a modified version of the Das and Van Soest estimator; see Das and Van Soest, 1999 and Dickerson et al. 2012).

where $f(\cdot)$ is the joint distribution function and $\mathbf{1}(\cdot)$ is the indicator function. The integral in equation (7) does not have a closed form solution; however, it can be numerically approximated by the Gauss-Hermite quadrature method and the parameters can then be estimated by maximum likelihood (Green, 2008;Boes and Winkelmann, 2010).

4. Data

The longitudinal data used in this study come from the China Health and Nutrition Survey (CHNS), which is one of the most widely-used surveys for micro-level research in China. The CHNS was designed as a time-cohort survey. By now, eight waves of CHNS data have been collected (for the years 1989, 1991, 1993, 1997, 2000, 2004, 2006, and 2009). The survey employed a multistage, random cluster design to draw a sample of households, covering both rural and urban areas of nine Chinese provinces that vary substantially in socio-economic indicators[3]. Because data for the latest wave (for the year 2009) is not yet fully available, we focus our study on the first seven waves of the survey. Because this study concentrates on urban China, the rural households have been dropped from our sample.

In the CHNS survey, households are asked what kind of fuel(s) they normally use for cooking. Although households may not rely on just one type of cooking fuel, this study focused on the choice of primary cooking fuel, which is the fuel most often used, as stated in each household's response to the survey. Firewood (including wood, sticks, straw, etc.), coal, and LNG are found to be three of the most commonly used primary cooking fuels among the urban households; they account for up to 83% of the pooled sample. Thus, we focus on the choice among these three cooking fuels. Consequently our dependent variable in the ordered probit model – household cooking fuel choice – would be choice of firewood, coal, and LNG, which are in order of efficiency, convenience to use, and modernity. Therefore, we assign

[3]The provinces are Liaoning, Heilongjiang, Jiangsu, Shandong, Henan, Hubei, Hunan, Guangxi, and Guizhou. See more details on the survey design at http://www.cpc.unc.edu/projects/china

$E = 0$ for firewood, $E = 1$ for coal, and $E = 2$ for LNG as the dependent variable. This is similar to the order in Farsi et al. (2007), which considered the cooking fuels in urban India in the order of firewood, kerosene, and LPG.

Given that our study focused on analyzing the determinants of primary cooking energy choice, we eliminated the observations for which important variables (including the primary cooking fuel choice, household income, energy price data, characteristics of household head, etc.) are not available. This produces our final sample of 3,425 pooled observations, with a total number of 1,525 households in this sample.[4]

From this sample, we find that the percentage of households using LNG as their primary cooking fuel increased dramatically over time, while the percentage of households using firewood or coal shows a clear tendency of decreasing. This implies that households are making a transition toward more efficient sources of primary cooking energy in urban China. For instance, the data indicate that, in 1989, around 75% of urban households used coal as their primary cooking fuel. This figure decreased dramatically to 26% in 2006. The proportion of households choosing firewood as their primary cooking energy decreased from 11.3% in 1989 to only 7% in 2006. At the same time, the proportion of households using LNG as their primary cooking fuel increased from 13.2% in 1989 to 44.7% in 1997 and rose further to 67% in 2006. These facts seem to suggest a tendency of switching in households' primary cooking fuels to more efficient energy.

We study the effect of household income because that has been found in the literature to be an important determinant of household fuel choice. The household income used in this study is already inflated to the year 2009, using Consumer Price Indexes, to make income comparable over different time periods (waves). The relationship between primary cooking fuel choices and household income level is presented in Figure 1. It can be seen that, as

[4] It should be noted that some of households appeared for only some waves rather than all waves. One may raise the issue of attrition, which, however, is not found to be systematic.

household income increases, people are more likely to choose the fuels that are ranked higher in terms of efficiency or modernity, i.e., LNG, as their primary cooking fuels, and are less likely to choose the fuels that are ranked lower, i.e., firewood and coal.

< Figure 1 here>

Table 1 presents the descriptive statistics for socio-economic variables by cooking fuel choices. It can be observed from Table 1 that some trends exist in households' choice of primary cooking fuel. As well as household income, gender, education and job characteristics of household heads are associated with distinct differences between households that choose firewood as their primary cooking fuel and those that choose LNG as their primary cooking fuel. For instance, the average income for the households that choose LNG as their primary cooking fuel is over 70% higher than those that prefer firewood. Further, the proportion of female household heads in the "LNG" category is larger than that in the "firewood" category or that in the "coal" category.

Three dummy variables were used to represent the highest education attained by household heads: primary school degree, secondary school degree, and university (or higher) degree. As shown in Table 1, only 0.3% of the heads of the households choosing firewood as their primary cooking fuel have a university or higher degree, while the figure is about 9.7% for those choosing LNG. Though the differences in primary school degree achievement are not as remarkable as those for the university degree, we can still observe that the proportion of household heads who completed only primary schooling is higher in the firewood category. Also, it can be seen that a higher share of household heads have a secondary school degree in the LNG category, compared with the firewood or coal category. All these facts seem to suggest that better educated people tend to choose more efficient fuels.

The job characteristic of a household head is represented by a dummy variable indicating whether the head was employed in the public sector[5] at the time of the survey. The differences

[5] The public sector here includes government departments, state service/institutes, and state-owned enterprises.

related to this variable can also be clearly observed in Table 1. Specifically, only 11.6% of the household heads who choose firewood as the primary cooking fuel are employed in the public sector, whereas the figure is 35.8% for the household heads choosing coal and 37.5% for the household heads choosing LNG. This indicates a possible relationship between public sector employment and household cooking fuel choice. In terms of household size, the descriptive statistics show that the households choosing LNG as their primary cooking fuel tend to be smaller on average, compared with those choosing firewood or coal as their primary cooking fuel.

< Table 1 here>

In the literature, fuel prices have also been found to be potential determinants of household cooking fuel choices. Because the prices of firewood (wood, straw, etc.) are not available in the survey, only the prices of coal and LNG are considered in the final analysis. Moreover, the fuel prices collected in the survey are at the community level, which implies that all the households in one community face the same price. In addition, we inflate the prices of coal and LNG in the data set to the year 2009 (by using the community-level inflation indexes which are included the data set) to make them comparable over different time periods (waves). Furthermore, it is likely that income grows with experience (age) and therefore the age variable may capture some of the income effect in the regressions. To avoid this, we replace the age variable with the birth year of household head.[6] The variables used in the econometric analysis that follows are listed in Table 2, where the descriptive statistics are for the entire sample. In addition, the within and between variations of the variables are shown in Table A1 in the appendix, from which one can see that, although there are both

[6] Thanks to an anonymous reviewer for pointing this out and inspiring us to do such a transformation.

within and between variations for each variable, the within (time) variations are less remarkable than the variations across households.[7]

< Table 2 here>

5. Empirical Results

Results from the maximum likelihood estimation for the standard ordered probit (OPROBIT), generalized ordered probit (GOPROBIT), random effect generalized ordered probit (RE-GOPROBIT) and correlated random effect generalized ordered probit (CORR-REGOPROBIT) models [8] are presented in Table 3. To control for the time trend of the panel data and regional differences in fuel choices, we include wave and area (province) dummies in all the regressions. From Table 3, it can be seen that, in each generalized model, two parameter vectors (β_1 and β_2) are estimated. The parameter vector β_1 refers to estimated coefficients of the determinants for the coal category compared to the base category (firewood). Vector β_2 is for LNG. The explanatory variables used in all these regressions are displayed in Table 2. The marginal effects of the variables are presented in Tables 4 and 5.

Comparing the estimated results of two cross-sectional ordered probit models (Oprobit and GOPROBIT), from Table 3 (columns 1-3), we can see some differences in size and signs of the estimated coefficients for some of the explanatory variables. For instance, the coefficient for coal price shows a large difference between the estimates from OPROBIT and those from GOPROBIT. The coefficients for coal price in the two parameter vectors (β_1 and β_2) of GOPROBIT have opposite signs and their magnitudes are nearly twice as large as the estimates from OPROBIT. The positive sign of the estimated coefficient for coal price in the OPROBIT implies that a higher price of coal induces households to choose higher-ranked

[7] One may raise the question of why variables such as gender vary over time. This is due to the change of heads in some of the households across survey waves.

[8] The generalized ordered probit model, random effect generalized ordered probit model and correlated random effect generalized ordered probit model were estimated by maximum likelihood estimation using the Stata commands "goprobit" and "regoprob," respectively.

fuel(s). From Table 4, one can see the difference in the estimated marginal probability effects of coal price on the choice of different fuel types. The marginal effect of coal price on the choice of firewood is negative 0.8% in the standard ordered model, while it is positive 1.7% in the generalized ordered probit model. This implies that the marginal effects from the two estimators are different in sign and magnitude, indicating that the parallel regression assumption of the standard ordered probit model may not hold in our context. A more formal test for this assumption is provided below.

< Tables 3 and 4 here>

An overall Wald test on the generalized ordered probit model against the standard model also suggests that we can reject the parallel regression assumption (χ^2_{25} =726.45 (p-value=0.000) for GOPROBIT, χ^2_{25} =421.75 (p-value=0.000) for RE-GOPROBIT and χ^2_{31} =416.75 (p-value=0.000)) for CORR-REGOPROBIT). In addition, following Pfarr et al. (2010), a Wald test is applied to each variable to identify which variables have heterogeneous distributional impacts. As can be seen in Table A2 in the appendix, the null hypothesis of equal coefficients can be rejected for 19 out of the 25 variables (including year and province dummies) at the 10% level of significance, while the null hypothesis can be accepted for the following variables: price of LNG, household head marital status, education dummies, and the dummy indicating whether or not the household is in Hubei province.

While the results from the cross-sectional models (OPROBIT and GOPROBIT) can give some preliminary information on the factors that may affect the choice of cooking fuels, they are generally considered inefficient and inconsistent due to the potential unobserved individual heterogeneity, which can be addressed using the panel data models. In Table 3 (columns 4 and 5), we present results from the random effect generalized ordered probit model (RE-GOPROBIT), which controls the unobserved heterogeneity. As shown in Table 3, the estimated correlation coefficient of the composite error term, rho (ρ =0.49), is statistically significant, which implies significant unobserved heterogeneity in households' fuel choices and the need to control for it. In addition, comparing the GOPROBIT and RE-GOPROBIT results, the estimated coefficients (β_1 and β_2) of all the socio-economic variables (excluding the year and province dummies) are generally higher for RE-GOPROBIT. This difference may be attributed to the control for the unobserved heterogeneity.

While RE-GOPROBIT accounts for individual unobserved heterogeneity, its implicit assumption of no correlation between unobserved heterogeneity and the explanatory variables is often unlikely to hold. For example, a household head who is born with persistent personal motivation may work more hours and earn money (income) that enables him/her to purchase more efficient, modern and convenient fuels. Following Boes and Winkelmann (2010), Chamberlain (1980) and Mundlak (1978), it is possible to control the bias from the possible correlation between the unobserved heterogeneity and the explanatory variables by including the averages of the time-varying regressors in the model. According to Ferrer-i-Carbonell (2005), this approach will yield similar results to the standard fixed effects approaches that factor out the fixed effects from the estimation.

Results from the random effect generalized ordered probit with Mundlak transformation, i.e., the correlated random effects generalized ordered probit model (CORR-REGOPROBIT), are presented in Table 3 (columns 6 and 7). As shown in Table 3, the mean values of time-varying covariates are jointly significant, implying the relevance of the Mundlak approach in controlling the bias from unobserved heterogeneity. In addition, comparing the estimated coefficients of RE-GOPROBIT and CORR-REGOPROBIT, we can observe the differences in size and significance for the following variables: income, public sector employment, all education dummies and household size. Considering the importance of allowing the correlation between the unobserved heterogeneity and explanatory variables, we refer mainly to the correlated random effect generalized ordered probit (CORR-REGOPROBIT) results and the corresponding marginal effects in our discussion that follows.

From the CORR-REGOPROBIT regression results, it is evident that household economic status, head's characteristics, fuel prices and year (wave) dummy variables play important roles in determining the household's primary cooking fuel choice in urban China. Beginning our analysis with the economic status of the household, one can see from Table 3 that this variable is positive in the two parameter vectors (β_1 and β_2) of the CORR-REGOPROBIT columns. Likewise, the marginal effect of household income, which is presented in Table 5, is positive for the probability of choosing coal and LNG, when evaluated at the sample mean. These two positive estimates convey the message that, as the income of households rises, they prefer to use coal and LNG rather than firewood as their primary cooking fuels, though neither marginal effect estimate is statistically significant. Nevertheless, as can be seen from Table 5, the marginal probability effect of income on the choice of firewood is negative and statistically significant. In general, a one-unit increase in household income (log) will on average decrease the probability of choosing firewood by 1.4%. The marginal effect results from OPROBIT, GOPROBIT and RE-GOPROBIT also suggest the negative effect of income on the choice of firewood and the positive effect of income on LNG, as can be seen in Tables 4 and 5. The general finding that households with higher income are less likely to choose the low-ranked energy sources is consistent with the findings from earlier studies (Heltberg, 2004; Heltberg, 2005; Farsi et al. 2007; Cooke et al., 2008; Mekonnen and Köhlin, 2008).

< Table 5 here>

Consistent with previous studies (Heltberg 2004; Heltberg, 2005; Farsi et al. 2007; Mekonnen and Köhlin, 2008; Gebreegziabher et al., 2012), fuel prices are also found to be important in determining cooking energy choices in urban China. As we can see from the results of CORR-REGOPROBIT in Table 3 and its corresponding marginal effect (Table 5), a higher coal price decreases the probability of choosing coal as the primary cooking energy and increases the probability of choosing firewood and LNG. More specifically, a one-unit increase in the coal price (log) will decrease the average share of households choosing coal as their primary cooking fuel by 4.8%, while increasing the share of those choosing firewood and LNG by 1.6% and 3.2%, respectively. We can see similar results from the RE-GOPROBIT and GOPROBIT marginal effect estimates of coal price. However, in the standard ordered probit model (OPROBIT), a higher coal price is found to be associated with a lower possibility of choosing firewood. The difference may reflect the fact that the OPROBIT model does not take into account potential heterogeneous effects of the explanatory variables across the distribution of cooking fuel choices, while the generalized models do.

An increase in LNG price, on the other hand, decreases households' choice of LNG (own price effect) but increases their choice of coal (substitution effect). It can be observed from the CORR-REGOPROBIT marginal effect (Table 5) that a one-unit increase in the LNG price (log) will increase the average share of households that choose coal as the primary cooking fuel by 8.4%, while decreasing the share of those choosing LNG by 6.5%. However, the marginal effect of such an increase in the LNG price on the probability of choosing firewood is insignificant. Similar to the coal price effect discussed above, we also see a different result in the standard ordered probit model, where a higher LNG price is shown to have a positive marginal effect on the probability of choosing firewood; however, this marginal effect is negative and statistically insignificant at the conventional level in all the three generalized models (GOPROBIT, RE-GOPROBIT and CORR-REGOPROBIT). The estimated results for the fuel price variables imply that price policies can play an important role in households' fuel transitions. Policies that decrease the prices of modern energy sources can have positive effects in reducing deforestation as well as indoor air pollution and its health impacts.

In many developing countries, it is more common to see women than men cooking, and hence they are more likely to be exposed to the health hazards of indoor air pollution from using dirty fuel sources. Our expectation is that, compared to the male-headed households, the decision-makers in female-headed households better understand the health risks and inconveniences of cooking with unclean fuel sources. Consistent with our expectation, all four models suggest that female-headed households are less likely to choose firewood or coal as their primary cooking fuel, and more likely to choose LNG. Referring to the marginal effect results of the CORR-REGOPROBIT model, female-headed households are, on average, 8.8% more likely to choose LNG as their primary cooking fuel, and 5.9% less likely to choose firewood, than are households with male heads. This implies that greater empowerment of women in the household can be helpful in increasing the usage of cleaner household energy in China.

In addition, the job characteristics of a household head may also affect the household's preference for cooking fuel choices. The estimated coefficients and marginal effects of having a public sector employed head in the CORR-REGOPROBIT model are positive for choosing coal and LNG; they are statistically insignificant in this model but significant in all the cross-sectional models and also in the RE-GOPROBIT model. This difference may be due to the control of the correlation between the explanatory variables and the time-invariant unobserved heterogeneity in the CORR-REGOPROBIT model.

Education is an important policy tool to raise households' awareness about the benefits of clean energy sources and the risks of dirty fuel sources. This implies that a household head with a higher education level is expected to be more likely to choose clean energy sources. In this study, we use three dummy variables to represent the highest education attained by household heads: primary school degree, secondary school degree, and university (or higher) degree. Our results indicate that lower education levels (primary and secondary school) are insignificant as determinant of fuel choices. However, it can be observed that household heads having a university or higher degree are more likely to choose higher-ranked energy sources than those who do not have a university degree. From the marginal effect results of CORR-

REGOPROBIT displayed in Table 5, it can be seen that household heads having a university degree or higher are 22% more likely to choose LNG, compared with those without a university degree. This effect of education is consistent with earlier studies on fuel demand (Jiang and O'Neill, 2004; Heltberg, 2004; Heltberg, 2005; Farsi et al., 2007; Mekonnen and Köhlin, 2008).

Previous studies find mixed results on the effect of household size on fuel choice and fuel switching (Heltberg, 2004; Heltberg, 2005; Ouedraogo, 2006; Farsi et al. 2007). For example, Ouedraogo (2006) suggests that, in urban Burkina Faso, households with fewer members are more likely to adopt LPG and less likely to use firewood for cooking. However, Heltberg (2004) found an insignificant effect of household size on fuel switching. In this study, we find that the effect of household size is insignificant for firewood and coal but it is significant for LNG. According to the marginal effect results from CORR-REGOPROBIT (Table 5), increasing the household size by one more person is associated with a 1.4% increase in the probability of choosing LNG. This may suggest that clean cooking energy such as LNG can be more easily adopted in a larger household. This may be due to the greater economies of scale with a larger household size.

As can be seen from Table 5, the marginal effect of the wave dummies show that more and more people are shifting from firewood and coal toward LNG. These wave dummies account for the effects of policy changes or other phenomena over time (other than the change in socio-economic characteristics) that could make households shift their energy choices. For example, the shift to LNG may be associated with increased access to LNG over time. Yang et al. (2014) documented an increasing trend in LNG pipeline networks in urban China since 1998. Furthermore, the reduction in the usage of firewood in urban China over time may also be related to the introduction of more restrictive forest policies such as the Natural Forest Conservation Program (NFCP) from 1998 onward (Zhang et al., 2000), which stipulates the protection of existing natural forests from excessive cutting, thereby reducing the supply of firewood.

Ordered probit models assume the ordering of different fuels in terms of efficiency and convenience to use. As discussed in the empirical strategy section, one may argue that the households' actual ranking of the fuels may not be obvious and hence the multinomial logit model may be used alternatively. Nonetheless, the generalized ordered probit/logit model is preferable in cases where ordering is not "a priori obvious" (Anderson, 1984) and a multinomial logit model can result in inefficient estimates if the ordering is inherent in the household fuel preference (Boes and Winkelmann, 2010). Yet, for completeness, we provide in the appendix (Table A3) the result from the random effect and correlated random effect multinomial logit models. Comparing Tables 3 and A3, it can be seen that the correlated random effect generalized ordered probit and the correlated random effect multinomial logit models result in different results in terms of significance of variables. For instance, the two models are different in terms of significance for income, coal price, LNG price, household size, and education (university degree). However, in terms of the sign of estimated coefficients, the two models are mostly the same.

Furthermore, we also provide in the appendix (Table A4) the results from the standard fixed effects ordered logit models. From Table A4, one can see a difference in the magnitude and significance of the estimated coefficients between the standard (non-generalized) random effects and fixed effects ordered logit models. However, one should be aware that both models are based on the parallel regression assumption. As mentioned above, this assumption has been rejected using the overall Wald test and it is violated by most of the explanatory variables (19 out of 25) in the model (see Table A2).

6. Conclusion and Policy Implications

Households' transition to modern energy sources can reduce the health and environmental impacts caused by the use of traditional energy. Understanding the determinants of household fuel choice can provide policy implications for encouraging the adoption of cleaner and more efficient fuels in households. As the largest developing country in the world, China's evidence on this issue is of great interest and importance for drawing policy implications useful for other developing countries. Unlike previous studies on China, most of which are based on aggregate statistics or cross-sectional data from household surveys in a certain province or county, this paper employed panel data from a nationwide survey (CHNS) to study the determinants of household fuel choice in urban China. Ordered probit models were employed in this study to take into account the potential ordering of different fuels in terms of efficiency or convenience to use, as in Farsi et al. (2007). Moreover, as mentioned above, we also made extensions to the applications of ordered discrete choice models to household fuel choice in terms of relaxing the parallel regression assumption and controlling the potential correlation between the explanatory variables and unobserved heterogeneity.

Our results indicate the heterogeneous effects of the explanatory variables across the distribution of different cooking fuels, which supports the use of a generalized ordered probit model. Also, the random effects generalized ordered probit with Mundlak transformation generates results that are significantly different from those that are based on the standard random effects and cross-sectional methods.

Furthermore, the results indicate that higher income leads to a lower probability of choosing low-ranked cooking fuel sources, which is in line with the traditional energy ladder hypothesis. Meanwhile, the results also show that, in addition to income, socio-demographic factors, such as gender and education of the household heads, are also important in determining the choice of primary cooking fuel in urban Chinese households. Thus, consistent with other recent studies (Masera et al., 2000; Heltberg, 2005; Farsi et al., 2007), our results suggest that fuel choice is not determined merely by a household's economic condition.

Coal and LNG prices were also found to be important in household choices of primary cooking energy. An increase in the coal price is associated with a statistically significant decrease in the probability of choosing coal but a significant increase in the probability of choosing LNG or firewood as the primary cooking fuel. As expected, a higher LNG price will reduce the probability of choosing LNG and increase the probability of choosing coal for the primary cooking fuel. From a policy point of view, these results indicate that interventions that reduce the price of LNG can encourage households to use it as the primary cooking fuel and reduce the usage of dirty fuels.

The tendency that households with female heads are more likely to choose LNG as the primary cooking fuel and less likely to choose firewood implies that greater empowerment of women in the household can be helpful in increasing the usage of clean energy in urban China. In addition, the result that more education for household heads increases the probability of choosing LNG suggests that promotion of higher levels of education can be an effective way to encourage households to choose clean energy as the primary cooking fuel.

The estimated results of the year dummies indicate that more and more people are shifting over time from firewood and coal toward LNG. The shift to LNG may also be associated with increased access to LNG over time, such as an increase in pipeline networks in urban China. In addition, the reduction in the use of firewood in urban China over time may also be related to the introduction of more restrictive forest policies such as the Natural Forest Conservation Program (NFCP).

However, this paper is not without limitations. For example, due to lack of information on the proportion of each fuel for the households that use multiple fuels, this study focused on the choice of primary cooking fuel and did not analyze multiple fuel use. Therefore, a direction for future research can be more comprehensive modeling of households' decision-making on cooking fuels, with consideration of all the fuels that a household can use. This will require richer data on households' cooking fuel choices.

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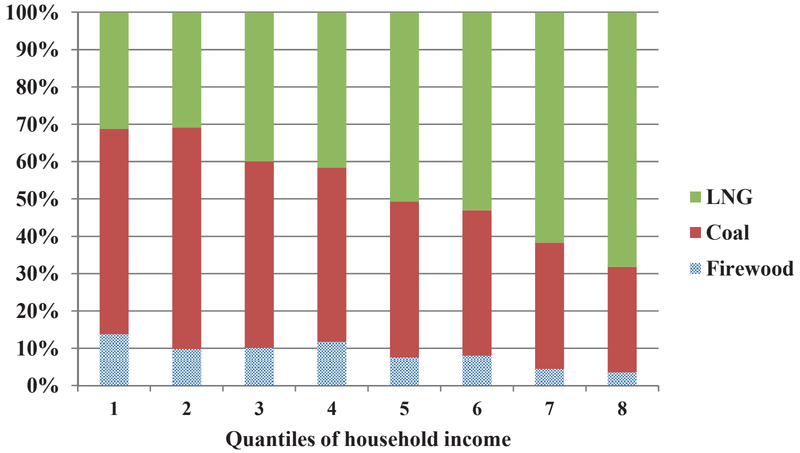

Fig.1 Primary cooking fuel by quantiles of household income

List of Tables

Table 1. Means of major variables by primary cooking fuel choice

	Firewood E=0	Coal E=1	LNG E=2
Household income	15149.99	18547.94	26436.44
Birth year of household head	1948.207	1943.754	1947.768
HHs with a female head	0.143	0.252	0.271
HH head married	0.874	0.840	0.858
HH head employed in public sector	0.116	0.358	0.375
HH head with primary education	0.214	0.218	0.163
HH head with secondary education	0.415	0.394	0.547
HH head with university (or higher) educ.	0.003	0.018	0.097
HH size (number of persons in HH)	4.051	3.627	3.270

Table 2. Descriptive statistics

Variable	Mean	Std. Dev.	Minimum	Maximum
Household income	21975.950	24185.540	5.160	412145.700
Coal price	0.541	0.788	0.035	4.674
LNG price	78.582	19.466	26.076	127.800
Birth year of household head	1946.029	14.345	1898	1988
HHs with a female head	0.251	0.434	0	1
HH head married	0.851	0.356	0	1
HH head employed in public sector	0.345	0.476	0	1
HH head with primary education	0.192	0.394	0	1
HH head with secondary education	0.468	0.499	0	1
HH head with university (or higher) educ.	0.054	0.227	0	1
HH size (number of persons in HH)	3.495	1.384	1	12

Table 3. Estimation results of ordered probit (OPROBIT), generalized ordered probit (GOPROBIT), random effect generalized ordered probit (RE-GOPROBIT) and correlated random effect generalized ordered probit (CORR-REGOPROBIT)

	OPROBIT	GOPROBIT		RE-GOPROBIT		CORR REGOPROBIT	
VARIABLES		β_1	β_2	β_1	β_2	β_1	β_2
Household income (log)	0.201***	0.296***	0.212***	0.334***	0.214***	0.190***	0.030
	(0.026)	(0.042)	(0.029)	(0.057)	(0.038)	(0.071)	(0.048)
Coal price (log)	0.059**	-0.159***	0.126***	-0.211**	0.169***	-0.219***	0.165***
	(0.027)	(0.053)	(0.032)	(0.083)	(0.044)	(0.085)	(0.044)
LNG price (log)	-0.303**	0.075	-0.357**	0.244	-0.416**	0.260	-0.340*
	(0.125)	(0.261)	(0.153)	(0.391)	(0.201)	(0.401)	(0.204)
Year of birth	-0.008***	-0.015***	-0.006**	-0.018***	-0.007**	-0.017***	-0.009**
	(0.002)	(0.004)	(0.003)	(0.005)	(0.003)	(0.005)	(0.004)
HHs with a female head	0.351***	0.725***	0.337***	0.840***	0.493***	0.812***	0.461***
	(0.067)	(0.157)	(0.073)	(0.170)	(0.102)	(0.174)	(0.103)
HH head married	0.004	0.209	-0.043	0.124	-0.034	0.044	-0.098
	(0.077)	(0.162)	(0.088)	(0.192)	(0.120)	(0.198)	(0.121)
HH head employed in public sector	0.587***	0.889***	0.586***	0.917***	0.641***	0.214	0.010
	(0.058)	(0.107)	(0.071)	(0.150)	(0.093)	(0.214)	(0.125)
HH head with primary education	0.093	0.074	0.154*	0.102	0.192*	0.075	-0.056
	(0.069)	(0.124)	(0.081)	(0.161)	(0.116)	(0.282)	(0.197)
HH head with secondary education	0.380***	0.393***	0.505***	0.601***	0.717***	0.498	0.204
	(0.072)	(0.132)	(0.081)	(0.155)	(0.115)	(0.338)	(0.209)
HH head with university (or higher) educ.	1.024***	1.289***	1.112***	1.942***	1.581***	-0.375	1.151**
	(0.153)	(0.391)	(0.165)	(0.597)	(0.228)	(1.740)	(0.508)
HH size (number of persons in HH)	-0.095***	-0.134***	-0.083***	-0.166***	-0.067**	0.026	0.073*
	(0.019)	(0.034)	(0.022)	(0.042)	(0.030)	(0.065)	(0.042)

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Continued from Table 3

VARIABLES	OPROBIT	GOPROBIT β_1	GOPROBIT β_2	RE-GOPROBIT β_1	RE-GOPROBIT β_2	CORR-REGOPROBIT β_1	CORR-REGOPROBIT β_2
_Iwave_1991	0.390***	0.036	0.598***	-0.311	0.768***	-0.301	0.845***
	(0.078)	(0.220)	(0.113)	(0.303)	(0.183)	(0.311)	(0.188)
_Iwave_1993	0.442***	0.112	0.759***	0.132	1.179***	0.251	1.258***
	(0.082)	(0.156)	(0.126)	(0.244)	(0.188)	(0.249)	(0.193)
_Iwave_1997	0.738***	-0.037	1.278***	-0.164	1.816***	-0.078	1.920***
	(0.092)	(0.174)	(0.135)	(0.279)	(0.199)	(0.287)	(0.206)
_Iwave_2000	0.972***	0.499***	1.416***	0.562**	2.045***	0.704***	2.133***
	(0.083)	(0.158)	(0.124)	(0.241)	(0.193)	(0.248)	(0.199)
_Iwave_2004	1.092***	0.905***	1.503***	0.994***	2.124***	1.089***	2.197***
	(0.093)	(0.177)	(0.134)	(0.264)	(0.204)	(0.271)	(0.210)
_Iwave_2006	1.318***	0.856***	1.732***	0.985***	2.452***	1.115***	2.543***
	(0.104)	(0.186)	(0.139)	(0.259)	(0.215)	(0.266)	(0.221)
Constant	-15.697***	25.817***	11.034**	30.489***	11.652*	27.039***	12.548*
	(4.375)	(7.556)	(4.858)	(9.181)	(6.680)	(9.449)	(6.827)
Province dummies	YES	YES		YES		YES	
Rho				0.490*** (0.035)		0.479*** (0.035)	
Overall Wald test for parallel regression assumption: χ^2 (p-value)		726.45 (0.000)		421.75(0.000)		416.75(0.000)	
Joint test for the mean of time-varying variables: χ^2 (p-value)						125.27(0.000)	
Observations	3,425	3,425		3,425		3,425	

Standard errors in parentheses ***p<.01,**p<0.5,*p<0.1

The parameter vector β_1 refers to estimated coefficients of the determinants for the coal category compared to the base category (firewood). Vector β_2 is for LNG.

Table 4. Marginal effects from standard ordered probit model and generalized ordered probit

	Oprobit marginal effects			GOPROBIT marginal effects		
VARIABLES	Firewood	Coal	LNG	Firewood	Coal	LNG
Household income (log)	-0.026***	-0.035***	0.061***	-0.031***	-0.027***	0.058***
	(0.004)	(0.005)	(0.008)	(0.005)	(0.007)	(0.008)
Coal price (log)	-0.008**	-0.010**	0.018**	0.017***	-0.051***	0.034***
	(0.003)	(0.005)	(0.008)	(0.005)	(0.010)	(0.009)
LNG price (log)	0.039**	0.053**	-0.091**	-0.008	0.106**	-0.098**
	(0.016)	(0.022)	(0.038)	(0.027)	(0.046)	(0.042)
Year of birth	0.001***	0.001***	-0.002***	0.002***	0.000	-0.002**
	(0.000)	(0.000)	(0.001)	(0.000)	(0.001)	(0.001)
HHs with a female head	-0.045***	-0.061***	0.106***	-0.075***	-0.017	0.092***
	(0.009)	(0.012)	(0.020)	(0.016)	(0.022)	(0.020)
HH head married	-0.001	-0.001	0.001	-0.022	0.033	-0.012
	(0.010)	(0.013)	(0.023)	(0.017)	(0.026)	(0.024)
HH head employed in public sector	-0.075***	-0.102***	0.177***	-0.092***	-0.068***	0.160***
	(0.009)	(0.010)	(0.017)	(0.011)	(0.019)	(0.019)
HH head with primary education	-0.012	-0.016	0.028	-0.008	-0.034	0.042*
	(0.009)	(0.012)	(0.021)	(0.013)	(0.022)	(0.022)
HH head with secondary education	-0.048***	-0.066***	0.115***	-0.041***	-0.097***	0.138***
	(0.009)	(0.013)	(0.021)	(0.014)	(0.021)	(0.022)
HH head with university (or higher) educ.	-0.131***	-0.179***	0.309***	-0.134***	-0.170***	0.304***
	(0.021)	(0.027)	(0.045)	(0.041)	(0.052)	(0.044)
HH size (number of persons in HH)	0.012***	0.017***	-0.029***	0.014***	0.009	-0.023***
	(0.003)	(0.003)	(0.006)	(0.004)	(0.006)	(0.006)

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Continued from Table 4

	Oprobit marginal effects			GOPROBIT marginal effects		
VARIABLES	Firewood	Coal	LNG	Firewood	Coal	LNG
_Iwave_1991	-0.050***	-0.068***	0.118***	-0.004	-0.160***	0.164***
	(0.010)	(0.014)	(0.024)	(0.023)	(0.036)	(0.031)
_Iwave_1993	-0.056***	-0.077***	0.134***	-0.012	-0.196***	0.208***
	(0.011)	(0.015)	(0.025)	(0.016)	(0.036)	(0.034)
_Iwave_1997	-0.094***	-0.129***	0.223***	0.004	-0.353***	0.350***
	(0.012)	(0.017)	(0.028)	(0.018)	(0.038)	(0.036)
_Iwave_2000	-0.124***	-0.170***	0.294***	-0.052***	-0.335***	0.387***
	(0.011)	(0.017)	(0.025)	(0.016)	(0.035)	(0.033)
_Iwave_2004	-0.139***	-0.190***	0.330***	-0.094***	-0.317***	0.411***
	(0.013)	(0.019)	(0.028)	(0.018)	(0.038)	(0.035)
_Iwave_2006	-0.168***	-0.230***	0.398***	-0.089***	-0.385***	0.474***
	(0.015)	(0.021)	(0.031)	(0.019)	(0.037)	(0.036)

Standard errors in parentheses ***p<.01,**p<0.5,*p<0.1

Table 5. Marginal effects from random effect generalized ordered probit model and correlated random effect generalized ordered probit model

	RE-GOPROBIT marginal effects			COR-REGOPROBIT marginal effects		
VARIABLES	Firewood	Coal	LNG	Firewood	Coal	LNG
Household income (log)	-0.025***	-0.018**	0.043***	-0.014***	0.008	0.006
	(0.004)	(0.007)	(0.008)	(0.005)	(0.009)	(0.009)
Coal price (log)	0.016**	-0.049***	0.034***	0.016***	-0.048***	0.032***
	(0.006)	(0.009)	(0.009)	(0.006)	(0.009)	(0.008)
LNG price (log)	-0.018	0.101**	-0.083**	-0.019	0.084*	-0.065*
	(0.029)	(0.044)	(0.040)	(0.029)	(0.044)	(0.039)
Year of birth	0.001***	0.000	-0.001**	0.001***	0.000	-0.002**
	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)	(0.001)
HHs with a female head	-0.063***	-0.035*	0.098***	-0.059***	-0.029	0.088***
	(0.013)	(0.020)	(0.020)	(0.013)	(0.020)	(0.019)
HH head married	-0.009	0.016	-0.007	-0.003	0.022	-0.019
	(0.014)	(0.025)	(0.024)	(0.015)	(0.024)	(0.023)
HH head employed in public sector	-0.068***	-0.059***	0.128***	-0.016	0.014	0.002
	(0.011)	(0.018)	(0.018)	(0.016)	(0.026)	(0.024)
HH head with primary education	-0.008	-0.031	0.038*	-0.005	0.016	-0.011
	(0.012)	(0.022)	(0.023)	(0.021)	(0.040)	(0.038)
HH head with secondary education	-0.045***	-0.098***	0.143***	-0.036	-0.003	0.039
	(0.012)	(0.020)	(0.022)	(0.025)	(0.042)	(0.040)
HH head with university (or higher) educ.	-0.145***	-0.169***	0.315***	0.027	-0.248	0.220**
	(0.044)	(0.054)	(0.043)	(0.127)	(0.159)	(0.097)
HH size (number of persons in HH)	0.012***	0.001	-0.013**	-0.002	-0.012	0.014*
	(0.003)	(0.006)	(0.006)	(0.005)	(0.009)	(0.008)

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Continued from Table 5

	RE-GOPROBIT marginal effects			COR-REGOPROBIT marginal effects		
VARIABLES	Firewood	Coal	LNG	Firewood	Coal	LNG
_Iwave_1991	0.023	-0.176***	0.153***	0.022	-0.184***	0.162***
	(0.023)	(0.041)	(0.036)	(0.023)	(0.041)	(0.035)
_Iwave_1993	-0.010	-0.225***	0.235***	-0.018	-0.223***	0.241***
	(0.018)	(0.039)	(0.036)	(0.018)	(0.038)	(0.035)
_Iwave_1997	0.012	-0.374***	0.361***	0.006	-0.374***	0.368***
	(0.021)	(0.040)	(0.037)	(0.021)	(0.040)	(0.036)
_Iwave_2000	-0.042**	-0.365***	0.407***	-0.052***	-0.357***	0.409***
	(0.018)	(0.037)	(0.034)	(0.018)	(0.037)	(0.034)
_Iwave_2004	-0.074***	-0.348***	0.423***	-0.080***	-0.341***	0.421***
	(0.020)	(0.040)	(0.037)	(0.020)	(0.039)	(0.036)
_Iwave_2006	-0.074***	-0.414***	0.488***	-0.082***	-0.406***	0.487***
	(0.019)	(0.039)	(0.038)	(0.019)	(0.039)	(0.037)

Standard errors in parentheses ***p<.01,**p<0.5,*p<0.1

Appendix. Supplementary figures and tables

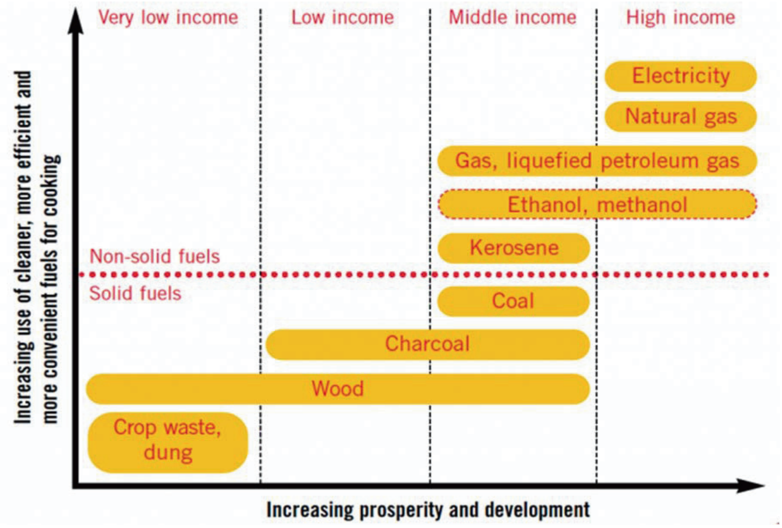

Fig. A1. Household energy and development are inextricably linked [Roser, 2014]

Table A1. Within and between variations of explanatory variables

Variable		Mean	Std. Dev.	Observations
Household income	overall	21975.95	24185.54	N = 3425
	between		19605.49	n = 1525
	within		15905.78	T-bar = 2.2459
Coal price	overall	0.541242	0.787806	N = 3425
	between		0.654759	n = 1525
	within		0.582713	T-bar = 2.2459
LNG price	overall	78.58188	19.46637	N = 3425
	between		17.85693	n = 1525
	within		10.80009	T-bar = 2.2459
Year of birth	overall	1946.029	14.34541	N = 3425
	between		14.57212	n = 1525
	within		3.297023	T-bar = 2.2459
HHs with a female head	overall	0.251387	0.433874	N = 3425
	between		0.419536	n = 1525
	within		0.168022	T-bar = 2.2459
HH head married	overall	0.851387	0.355759	N = 3425
	between		0.325577	n = 1525
	within		0.185118	T-bar = 2.2459
HH head employed in public sector	overall	0.345402	0.475568	N = 3425
	between		0.426019	n = 1525
	within		0.260885	T-bar = 2.2459
HH head with primary education	overall	0.191825	0.393794	N = 3425
	between		0.358223	n = 1525
	within		0.177307	T-bar = 2.2459
HH head with secondary education	overall	0.468321	0.499068	N = 3425
	between		0.475282	n = 1525
	within		0.18174	T-bar = 2.2459
HH head with university (or higher) educ.	overall	0.054307	0.226655	N = 3425
	between		0.243287	n = 1525
	within		0.082336	T-bar = 2.2459
HH size (number of persons in HH)	overall	3.494891	1.384173	N = 3425
	between		1.258899	n = 1525
	within		0.709637	T-bar = 2.2459

Table A2. Testing the parallel regression assumption for each variable

Variable	P-value
Household income (log)	0.01876
Coal price (log)	0.00000
LNG price (log)	0.11530
Year of birth	0.00749
HHs with a female head	0.03854
HH head married	0.46520
HH head employed in public sector	0.09695
HH head with primary education	0.59690
HH head with secondary education	0.56440
HH head with university (or higher) educ.	0.39930
HH size (number of persons in HH)	0.04797
wave_1991	0.00050
wave_1993	0.00027
wave_1997	0.00000
wave_2000	0.00000
wave_2004	0.00014
wave_2006	0.00000
Heilongjiang province	0.00465
Jiangsu province	0.00140
Shandong province	0.00000
Henan province	0.00000
Hubei province	0.8005
Hunan province	0.00000
Guangxi province	0.00002
Guizhou province	0.00000

Table A3. Estimates of random effect and correlated random effect multinomial logit models

VARIABLES	Random Effect Multinomial logit β_1	β_2	Correlated Random Effect Multinomial logit β_1	β_2
Household income (log)	0.509***	0.806***	0.397**	0.366**
	(0.141)	(0.146)	(0.158)	(0.163)
Coal price (log)	-0.325*	-0.090	-0.298	-0.075
	(0.186)	(0.185)	(0.206)	(0.205)
LNG price (log)	-2.413**	-2.999***	-2.310**	-2.811***
	(1.011)	(1.014)	(1.003)	(1.007)
Year of birth	-0.048***	-0.052***	-0.036**	-0.044***
	(0.014)	(0.014)	(0.015)	(0.015)
HHs with a female head	1.462***	1.877***	1.564***	1.954***
	(0.365)	(0.367)	(0.408)	(0.416)
HH head married	0.345	0.232	0.112	-0.057
	(0.388)	(0.396)	(0.432)	(0.436)
HH head employed in public sector	1.824***	2.633***	0.558	0.467
	(0.373)	(0.379)	(0.430)	(0.440)
HH head with primary education	0.213	0.451	0.305	0.271
	(0.324)	(0.338)	(0.491)	(0.521)
HH head with secondary education	0.440	1.293***	0.915	1.127
	(0.399)	(0.399)	(0.701)	(0.724)
HH head with university (or higher) educ.	2.861*	4.650***	-1.648**	-0.353
	(1.739)	(1.717)	(0.727)	(0.805)
HH size (number of persons in HH)	-0.260**	-0.372***	-0.044	0.046
	(0.107)	(0.112)	(0.144)	(0.149)
_Iwave_1991	-0.679	0.148	-0.686	0.256
	(0.698)	(0.711)	(0.778)	(0.790)
_Iwave_1993	-0.466	0.623	-0.481	0.715
	(0.498)	(0.513)	(0.579)	(0.592)
_Iwave_1997	-1.731***	0.374	-1.709***	0.532
	(0.603)	(0.620)	(0.652)	(0.667)
_Iwave_2000	-0.153	2.142***	-0.008	2.434***
	(0.493)	(0.513)	(0.545)	(0.562)
_Iwave_2004	0.591	3.008***	0.616	3.155***
	(0.505)	(0.523)	(0.554)	(0.571)
_Iwave_2006	1.256**	4.052***	1.442**	4.396***
	(0.596)	(0.602)	(0.630)	(0.640)
Constant	99.499***	107.845***	72.140**	83.355***
	(26.655)	(26.712)	(29.668)	(29.616)
Standard deviation of the random coefficients			2.863***	3.193***
			(0.354)	(0.541)
Observations	3,425		3,425	

Standard errors in parentheses ***p<.01,**p<0.5,*p<0.1

Table A4. Estimates of fixed and random effect ordered logit models

VARIABLES	BUC Ordered Logit Fixed effects Coef(SE)	FF Ordered Logit Fixed effect Coef(SE)	Random Effect Ordered logit Coef(SE)
Household income (log)	0.174*	0.153*	0.351***
	(0.100)	(0.091)	(0.059)
Coal price (log)	0.186**	0.191*	0.169***
	(0.093)	(0.099)	(0.065)
LNG price (log)	-0.219	-0.120	-0.714**
	(0.473)	(0.496)	(0.302)
Year of birth	0.012	0.012	-0.015***
	(0.018)	(0.019)	(0.005)
HHs with a female head	0.861**	0.876**	0.845***
	(0.345)	(0.364)	(0.159)
HH head married	-0.029	0.086	0.018
	(0.323)	(0.330)	(0.180)
HH head employed in public sector	-0.218	-0.168	0.236
	(0.338)	(0.366)	(0.171)
HH head with primary education	0.280	0.189	1.030***
	(0.218)	(0.231)	(0.139)
HH head with secondary education	0.019	0.011	0.996***
	(0.451)	(0.442)	(0.174)
HH head with university (or higher) educ.	15.596***	16.319	2.627***
	(1.010)	(741.892)	(0.380)
HH size (number of persons in HH)	0.106	0.085	-0.171***
	(0.090)	(0.079)	(0.044)
_Iwave_1991	0.568	0.499	0.574***
	(0.362)	(0.371)	(0.218)
_Iwave_1993	1.677***	1.732***	1.053***
	(0.392)	(0.377)	(0.221)
_Iwave_1997	2.333***	2.388***	1.669***
	(0.426)	(0.402)	(0.235)
_Iwave_2000	3.008***	2.930***	2.228***
	(0.447)	(0.396)	(0.223)
_Iwave_2004	3.098***	3.016***	2.426***
	(0.477)	(0.428)	(0.248)
_Iwave_2006	3.729***	3.547***	3.025***
	(0.517)	(0.452)	(0.271)
Province dummies			Yes
Cut1			-31.989***
			(10.310)
Cut2			-27.540***
			(10.300)
Sigma			2.927***
			(0.358)
Observations	1,569	1,386	3,425

Note: Standard errors in parentheses; ***p<.01,**p<0.5,*p<0.1. BUC is the Baestschmann et al. (2011) “Blow-up and Cluster” fixed effects ordered logit estimator, and FF is the Ferrer-i-Carbonell and Frijters (2004) fixed effects Ordered Logit estimator

Paper IV

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Adoption and disadoption of electric cookstoves in urban Ethiopia: Evidence from panel data☆

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ABSTRACT

Previous studies on improved cookstove adoption in developing countries use cross-sectional data, which make it difficult to control for unobserved heterogeneity and investigate what happens to adoption over time. We use robust non-linear panel data and hazard models on three rounds of panel data from urban Ethiopia to investigate the determinants of adoption and disadoption of electric cookstoves over time. We find that the prices of electricity and firewood and access to credit are major determinants of adoption and transition. Our findings have important implications for policies aiming at promotion of energy transition and reduction of the pressure on forest resources in developing countries.

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1. Introduction

In this paper, we use rich household-level panel data spanning a decade to investigate the determinants of adoption and disadoption of an electric cookstove by households in urban Ethiopia. Nearly 2.5 billion people worldwide rely on biomass fuel such as firewood and charcoal for cooking (Legros et al., 2009). Such reliance on biomass and forest products has serious health and environmental implications. WHO (2009) documents that solid fuel use is responsible for about 2 million premature deaths per year and 3.3% of the global burden of disease, particularly for women and children. Solid fuels, often burned in inefficient stoves, put significant burdens on women and children who have to divert their time from education and income generating activities into cooking and fuelwood collection (Lewis and Pattanayak, 2012). Moreover, the use of firewood for cooking has been a prime cause of deforestation and environmental degradation (Allen and Barnes, 1985; Geist and Lambin, 2002; Hofstad et al., 2009; Köhlin et al., 2011), very often resulting in loss of biodiversity and disturbance of local ecosystems. Recent studies (e.g., Sagar and Kartha, 2007; Grieshop et al., 2011) also document that, on a per-meal-equivalent basis, burning of biomass fuel in inefficient stoves could contribute more to global warming than fossil fuel using stoves.

One important remedy for achieving the dual objectives of improving household outcomes – through reduction of health risks and effort in cooking and energy collection – and protecting the environment is transition to cleaner energy sources such as electricity and solar energy. However, such a transition is not straightforward (Gebreegziabher et al., 2012; Lewis and Pattanayak, 2012) and is conditioned on acquisition of appropriate cooking equipment, which often require substantial financial outlay by poor households. It would therefore be important to understand the factors associated with adoption and disadoption of modern cookstoves. Specifically, answering the question "what determines adoption and sustained use of clean energy using stoves?" would be useful in providing relevant information to policy makers who aim at promoting energy transition.

Using richer panel data and a richer econometric analysis than previously applied to this topic in a developing country, we are able to explore a larger set of possible determinants of adoption and disadoption of the "Electric Mitad", the primary cooking appliance used to prepare the main Ethiopian staple, injera. Mitad[1] is a flat pan about 45–60 cm in diameter with a 20–30 mm thick clay griddle operated with either electricity or biomass fuel (mainly firewood) to give fast heat required for a good injera. Baking injera, which is done twice a week by a typical Ethiopian household with each session lasting for about two hours, accounts for 60 percent of household energy consumption in Ethiopia (Gebreegziabher et al., 2012). The traditional mitad operated on a three-stone open fire, with about 85–90 percent of the energy wasted, has been one of the prime contributors to the high rate of deforestation and the intensifying shortage of energy in many parts of Ethiopia (Gebreegziabher, 2007). A household using even the most advanced biomass Mitad known as "Mirte" (which reduces biomass consumption by half compared to the traditional three-stone mitad) would need on average 260 kg of wood per year (Bess, 2012).[2]

Given the significant negative consequences of using biomass energy sources, analyzing the determinants of adoption of the Electric Mitad and the corresponding reduction in biomass fuel use would provide useful insights into the magnitude of the impact of energy transition on the biomass stock of the country. In addition, Ethiopia has in recent years been experiencing rapid economic growth (average real GDP growth rate of 11% per annum during 2004–2011), which also included expansion of infrastructure such as roads, schools and hydroelectric power plants (IMF, 2012). Because we use panel data collected on the same households spanning this interesting period of time, we are able to control for time-invariant unobserved household heterogeneity and estimate the parameters of our models consistently, using robust non-linear panel data models. We show that the price of electricity, the price of the alternative energy (firewood) and access to credit are the most important determinants of adoption of the Electric Mitad in urban Ethiopia. The panel data also enables us to examine transitions of households into and out of adoption of the appliance and investigate the relevant determinants

[1] See http://www.addisababamarket.com/wp-content/uploads/2013/11/mogogo.jpg
[2] In other words, the traditional three-stone mitad requires 520 kg wood/year, twice the wood of the Mirte Mitad.

of transitions. We find that transition into and out of adoption of the Electric Mitad is determined by the price of electricity and firewood, households' economic status, socio-economic characteristics and access to credit by household members.

The rest of the paper is structured in the following fashion. In section 2, we provide a brief survey of the literature on improved cookstove adoption. In section 3, we present a description of the correlated random-effects probit and the proportional hazard models. In section 4, we present the panel data and summary statistics of major variables. In section 5, we present and discuss our regression results and, in the final section, we conclude and discuss the policy implications.

2. A review of literature on improved stove adoption

Most previous studies on stove adoption in developing countries focus to a great extent on adoption of improved biomass cookstoves in rural areas using cross-sectional data. Lewis and Pattanayak (2012) undertake a comprehensive survey of the literature on improved cookstove adoption and fuel choice in developing countries based on 32 studies.[3] According to these authors, empirical literature on adoption studies in developing countries fails to take a systematic approach in analyzing the various determinants and consequently remains narrow, thin and scattered. In the paragraphs below, we present a brief survey of previous studies focusing on adoption of improved cookstoves and highlight existing knowledge gaps.

An early published study on adoption of improved stoves was undertaken by Amacher et al. (1992). These authors used both theoretical and empirical methods to analyze the adoption and efficient use of improved biomass stoves. In their theoretical analysis, they argued that, even though improved stoves have the potential to reduce fuelwood consumption and exposure to indoor air pollution, these gains are uncertain for households who make decisions considering new technologies. These gains also vary across households depending on their efficient use of the improved stoves. When considering these, households will compare these uncertain gains with the financial cost of improved stoves. Accordingly, the decision to purchase the stove and the choices regarding its efficient use depend on household attitudes regarding risk and their expectation of the uncertain gains from adoption. Amacher et al., test some of the results from their theoretical models using a sample of 99 rural households from Nepal and show that households living in high price regions, those expecting greater fuel savings, those with more risky capital, and educated households are more likely to adopt the new technology before the less endowed households.

Using a randomly selected sample of 300 households from Khartoum state, Sudan, El Tayeb Muneer and Mohamed (2003) used a multiple linear regression method to analyze the adoption rate and the factors affecting adoption of improved cookstoves in what they call a "patriarchal society". During the 1980s and 1990s, improved biomass stoves were one of several programs aimed at testing and disseminating energy-saving technologies implemented in Sudan. Their result suggests that, in a patriarchal society where most of the household decisions are made by the head of the household, men's characteristics are expected to be more important determinants of the households' decision to adopt. However, their empirical result shows that the personal characteristics of the female members of the household are more important, in particular the education of the housewife and other female members. This finding is in line with Kammen (1995), who pointed out that failure to take into consideration the nature of the division of labor and the decision-making process within African households would not help in developing appropriate improved biomass cookstoves at a quick pace nor enhance their adoption at satisfactory rates.

For many households in the developing world, the high fixed cost of improved stoves and limited access to credit are among the factors that impede adoption of improved stoves. Edwards and Langpap (2005) use survey data from rural and urban Guatemala and examine the effect of startup cost and credit constraint in fuel switching. Their analysis shows that the prices of a stove and its complement, fuel, have a negative effect on the adoption of a Liquefied Petroleum Gas (LPG) stove; the effect is more pronounced in rural than in urban areas. The price of wood has a positive effect on stove ownership,

[3] An earlier survey of the literature on diffusion of improved biomass cookstoves was undertaken by Barnes et al. (1994).

indicating that such stoves are normal goods. Access to credit also determines fuel wood consumption indirectly, through its effect on gas-using stove adoption. However, in their simulation result, the effect of credit is small. The authors suggest subsidizing households for the upfront cost of the gas-using stoves as a promising policy for reducing firewood consumption.

An interesting finding on adoption of improved biomass cookstoves and consumption of biomass fuel was documented by Nepal et al. (2010). Using comprehensive and nationally representative household level data from Nepal, these authors show that improved cookstoves have been followed by increased biomass fuel consumption due to what is called the "rebound effect",[4] which implies increase in frequency of cooking due to improved efficiency after introduction of improved cookstoves, and consequently increase in biomass fuel consumption. The authors stress the importance of improving availability of cleaner fuels to rural households to reduce biomass energy consumption and the associated adverse consequences. More recently, using household data from rural Pakistan, Jan (2012) confirmed the importance of improving awareness and institutional support by governments and NGOs to encourage adoption of improved biomass cookstoves.

Relevant studies addressing adoption of improved biomass stoves and modern stoves in urban Ethiopia include Gebreegziabher et al. (2012) and Beyene and Koch (2012). Gebreegziabher et al. (2012) use cross-sectional data on a sample of 350 urban households in Tigray, Ethiopia, and find that income (proxied by expenditure), age and education of heads, and family size have positive impacts on electric mitad adoption, while these variables have negative effects on adoption of biomass-using mitads. Beyene and Koch (2012), on the other hand, used cross-sectional household level data and recall data on duration of stove use among 1577 urban households and investigate the determinants of adoption of two types of improved biomass stoves ("Mirte", a biomass-using mitad, and "Lackech", a charcoal-using stove) using a duration model. They find that adoption rates of both stoves have been increasing over time, and that income and wealth are significant determinants of adoption, while substitute technologies tend to hinder adoption. These authors conclude by highlighting the importance of controlling for unobserved household heterogeneity, such as culture and perceptions, and the use of panel data that tracks and documents information on the same households over time to better understand the determinants of adoption of improved stoves.

From the foregoing survey of the literature on stove adoption in developing countries, we can draw the following two key observations. First, almost all previous studies use cross-sectional data, which makes it difficult to control for unobserved heterogeneity and investigate the state of stove adoption over time. Second, most studies focus on rural areas and the adoption of improved biomass cookstoves. However, given earlier findings that improved biomass cookstoves may not necessarily result in reduction in biomass fuel use, due to what is called the "rebound effect", and given the rapidly increasing electrification in developing countries, it would be important to understand the determinants of adoption of cookstoves that use clean energy (such as electricity) and which variables to target to promote energy transition. In this paper, we attempt to fill these research gaps by using unique household-level panel data spanning a decade from urban Ethiopia. In doing so, we control for a broader set of household-level characteristics, which are expected to affect the decision to acquire a modern cooking appliance.

3. Empirical strategy

3.1. Correlated random effects probit model

Standard microeconomic theory of the consumer postulates that the demand for a durable consumer good arises from the stream of services acquired from it. A certain cooking appliance is therefore chosen when the utility from it is higher than the utility from alternative appliances (Dubin and McFadden, 1984). Thus, the decision to adopt an electric mitad appliance by households in urban Ethiopia could be modeled using a panel binary choice model.

[4] Sorrell et al. (2009) review the literature on rebound effects in energy use in developing countries.

Let the latent model of electric mitad appliance adoption be specified as

$$m_{it}^* = x\prime_{it}\beta + \varepsilon_{it}, \quad i = 1, 2, \ldots, N; \; t = 1, \ldots, T \tag{1}$$

$$\varepsilon_{it} = \alpha_i + u_{it} \tag{2}$$

where m_{it}^* is a latent dependent variable; m_{it} is the observed binary outcome variable indicating adoption of electric mitad, defined as

$$m_{it} = \begin{cases} 1, & \text{if}\, m_{it}^* > 0; \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

x_{it} represents a vector of time-varying and time-invariant exogenous variables such as socio-economic characteristics of household heads and other members, prices of electricity and alternative fuels, etc., which influence m^*; β represents a vector of parameters to be estimated; ε_{it} is a composite error term which can be decomposed into α_i, a term capturing unobserved individual (household in our case) heterogeneity and $u_{it} \sim IN(0, \sigma_u^2)$, a random error term. The subscripts i and t refer to households and time periods, respectively. One can marginalize the likelihood function by assuming that, conditional on the x_{it}, the unobserved individual heterogeneity term $\alpha_i \sim IN(0, \sigma_\alpha^2)$, is independent of the x_{it}s and u_{it}.[5]

Assuming that the distribution of the latent variable m^*, conditioned on α_i, is independent normal (Heckman, 1981), the vector of parameters, i.e., the βs can be estimated easily. Thus,

$$Pr(m_{it} = 1 | \alpha_i, x_{it}) = Pr\left(\frac{u_{it}}{\sigma_u} > \frac{-x\prime_{it}\beta - \alpha_i}{\sigma_u}\right) = \Phi(\nu_{it}) \tag{4}$$

where

$$\nu_{it} = -\frac{(x\prime_{it}\beta + \alpha_i)}{\sigma_u} \tag{5}$$

and Φ is the distribution function of the standard normal variate. Consequently, the likelihood function to be maximized (which is marginalized with respect to α) is given by

$$\prod_i \left\{ \int_{-\infty}^{\infty} \prod_{t=1}^{T} \left[1 - \Phi\left(x\prime_{it}\beta^* + \sqrt{\frac{\lambda}{1-\lambda}}\alpha^*\right)\right]^{1-m_{it}} \times \left[\Phi\left(x\prime_{it}\beta^* + \sqrt{\frac{\lambda}{1-\lambda}}\alpha^*\right)\right]^{m_{it}} \phi(\alpha^*) d\alpha^* \right\}$$

where $\beta^* = \beta/\sigma_u$ and $\alpha^* = \alpha/\sigma_\alpha$. A standard software can be used to estimate β^* and λ, which are normalized on σ_u.[6]

However, it is unrealistic in many cases to assume that the time invariant unobserved individual heterogeneity α_i is independent of the observable variables x'_{it} $\forall$ i and t. It is, for example, possible that motivation or ability, which are captured by α_i, would be correlated with some of the observed right-hand side variables such as education or occupational characteristics, which would in turn introduce bias in the coefficient estimates. It is possible to estimate more precise β parameters by allowing for correlation following Mundlak (1978) and Chamberlain (1982), which involves including $x_i = (x_{i0}, \ldots, x_{iT})$, or alternatively averages of the x-variables over time as additional regressors in the model. The model works through respecification of the unobserved individual heterogeneity term – α_i – presented in Eq. (2) as:

$$\alpha_i = \psi + \bar{x}_i\xi + a_i, \quad a_i | \sim N(0, \sigma_a^2), \tag{6}$$

[5] A straightforward implication of this assumption is that the correlation between the composite error terms in two successive periods for household i is constant and given by: $\lambda = corr(\varepsilon_{it}, \varepsilon_{it-1}) = \frac{\sigma_\alpha^2}{\sigma_\alpha^2 + \sigma_u^2}$.

[6] One other applicable binary choice panel data estimator is the fixed effects logit model (Cameron and Trivedi, 2009). However, because it is based on a within transformation (which also drops any time invariant observable variables in x_{it}) and on variation in the dependent variable over time (which limits the number of observations to be used for estimation and consequently reduces our sample size significantly), we preferred not to use it.

where $\bar{x}_i$ is the average of the time-varying variables in x_{it}, $t = 1, \ldots, T$ and σ_a^2 is the variance of a_i in the equation $\alpha_i = \psi + \bar{x}_i\xi + a_i$. The resulting modification and estimation of the model using the maximum likelihood method would give the more realistic non-linear panel data model called the "correlated random-effects probit" model (Wooldridge, 2010). In this paper, we allow for correlation between α_i and x_{it} and estimate this model.

3.2. Discrete–time proportional hazard model

In order to study the transition of households from adoption to disadoption and vice versa, we use a discrete–time proportional hazard model. In the literature of event history models, the length of time spent in a particular state is referred to as a spell (duration or episode). In the context of electric mitad adoption, we focus on the analysis of adoption spells and the estimation of exit from adoption and entry into adoption hazards. Thus, this parametric method of estimating exit from and entry into adoption spells uses the probabilities of ending a spell to model the distribution of adoption spell durations.

Let $d = 1$ for households with completed spells of non-adoption (and hence moved into adoption) and $d = 0$ for those that were still in a non-adoption spell when observed. Thus, the proportion with completed non-adoption spells is the hazard rate for that round. The hazard rate reflects the risk of exit from non-adoption and corresponds to the "survivor rate", which shows the proportion of households remaining in non-adoption at that time (Jenkins, 1995). Consequently, a discrete–time hazard rate h_{it} can be specified as

$$h_{it} = prob(T_i = t | T_i \geq t; \quad X_{it}), \tag{7}$$

where X_{it} represents a vector of explanatory variables (either time-variant or invariant) and T_i is a discrete random variable representing the time at which a non-adoption spell ends. Thus, the likelihood of ending a non-adoption spell at $T_i = t$ and at $T_i > t$ can be given by [7]

$$prob(T_i = t) = h_{it} \times \prod_{k=1}^{t-1}(1 - h_{ik}) = \left[\frac{h_{it}}{(1 - h_{it})} \times \prod_{k=1}^{t}(1 - h_{ik}\right) \tag{8}$$

and

$$prob(T_i > t) = \prod_{k=1}^{t}(1 - h_{ik}) \tag{9}$$

respectively. The most common parametric form of the hazard model which has been used to analyze spells – the proportional hazard model – is given by

$$h_{it} = h_0(t)\exp(X\prime_{it}\beta), \tag{10}$$

where $h_0(t)$ is the baseline hazard function, which is assumed to be the same for all households under analysis, X'_{it} is a vector of explanatory variables,[8] and β is the vector of parameters to be estimated. It is possible to control for unobserved household heterogeneity by incorporating a multiplicative gamma-distributed random error term ν, which is assumed to be uncorrelated with any of the X variables, into the proportional hazard model given in Eq. (10) as

$$h_{it} = h_0(t)\nu_i\exp(X_{it}) = h_0(t)\exp[X_{it} + \log(\nu_i)]. \tag{11}$$

The corresponding discrete–time hazard function in the jth interval can then be given by

$$h_j(X_{ij}) = 1 - \exp\{-\exp[X\prime_{ij}\beta] + \gamma_j + \log(\nu_i)\}, \tag{12}$$

[7] See Jenkins (1995) for detailed derivation of Eqs. (10) and (11).

[8] This implies that, with the baseline hazard function h_0 remaining the same for all households, individual household hazard rates depend on the X variables.

where γ_j is the parameter of the baseline hazard. The log likelihood of the hazard function presented in Eq. (11) is the same as the log likelihood for a generalized linear model of the binomial family with a complementary log-log link (Jenkins, 1995).[9]

4. Data and description of variables

The data used in our empirical models comes from three rounds of the Ethiopian Urban Socio-economic Survey (EUSS) collected in the years 2000, 2004 and 2009. The first two waves of the data were collected by Addis Ababa University, Department of Economics, in collaboration with the University of Gothenburg, Department of Economics, from seven major urban areas of Ethiopia: the capital Addis Ababa, Awassa, Bahir Dar, Dessie, Dire Dawa, Jimma, and Mekelle.[10] The cities selected were believed to represent a significant proportion (about 90 percent) of the Ethiopian urban population. Initially, about 1500 households were distributed over the cities in proportion to the cities' population size. Once the sample size for each city had been set, the sample households were recruited from half of the kebelles (the lowest administrative units) in all woredas (districts) in each urban center. The panel data is one of the few African panel data sets which documents detailed socioeconomic information at both the household and individual level for a fairly long period of time.

The last wave of the data – EUSS 2009 – was collected by one of the authors in late 2008 and early 2009 from a sub-sample of the original sample in four cities – Addis Ababa, Awassa, Dessie, and Mekelle – comprising 709 households.[11] These cities were carefully selected to represent the major urban areas of the country and the original sample.[12] Out of the 709 households covered in the survey, 128 were new households randomly chosen and introduced in the sampling to investigate whether the panel households, which were formed back in 1994, still represent the Ethiopian urban population. Alem and Söderbom (2012) check for this and show that there is no systematic difference between the new households and the old panel households in the key household outcome indicator – welfare measured by per capita consumption expenditure – which implies that the panel households represent urban Ethiopia reasonably well. Alem (in press) and Alem et al. (2012) also show that the panel data did not result in biased results due to attrition since the start of the panel.

In estimating our correlated random effects model of adoption, we use the unbalanced panel data comprising all the 1100 households in the four urban areas surveyed in the 2000 and 2004 waves, and the 709 households surveyed in 2009. After excluding 46 households with missing information, this left us with about 2863 observations. In order to estimate our hazard functions of entry into and exit from adoption, we use information on 446 households which were surveyed in all the three waves.

We investigate the determinants of adoption of electric mitad appliance under four headings: economic variables, household head's characteristics, household-level variables, and city and time dummies. The economic variables include real per capita consumption expenditure and price of electricity[13] and alternative fuels (in our case, firewood). We computed aggregate household consumption expenditure by adding up reported household expenditure on food and non-food items. The non-food component of consumption includes expenditures on items such as clothing, footwear, energy, personal care, utilities, health and education. To correct for spatial and temporal price differences, we divided nominal consumption expenditure by carefully constructed price indices from the survey, and computed real consumption expenditure. We then divided real household level

[9] A logistic form of a non-proportional hazard specification is also common in empirical research. However, in most cases, given the fact that the logistic model converges to a proportional hazard model as the hazard rates become smaller, the two specifications yield similar estimates (Jenkins, 1995).

[10] Data was also collected from these cities in 1994, 1995, and 1997. However, detailed information on energy use and prices was not collected in these earlier waves. Refer to AAU & GU (1995) for details on sampling.

[11] Resource constraints prevented the author from surveying households in the other cities.

[12] See Alem and Söderbom (2012) for a detailed description of EUSS-2009.

[13] Having access to electricity could be a source of bias in analyzing the determinants of any electricity using appliance. In our case, however, because all the households are located in major urban areas, 99 percent of the households had access to electricity.

consumption expenditure by adult equivalent units to adjust for difference in needs and economies of scale in consumption.[14]

Electricity, the energy required to operate an electric mitad, is provided by the government-owned monopoly, Ethiopian Electric Power Corporation (EEPCo). Hydropower constitutes over 90 percent of electricity production in Ethiopia, the rest coming from self-contained systems generating electricity using diesel. The country has more than 45,000 megawatt (MW) potential of hydropower. However only 3.3 percent (around 1494 MW) of the total potential has been used so far (EEPCo, 2011). Currently, the Ethiopian government is going through major investments to build dams that can generate around 10,000 MW in the coming few years. The largest dam which is under construction, "Grand Millennium Dam," is expected to generate around 6000 MW electricity by the year 2014. Access to electricity in the country has increased over the last five years to 46%; however, currently, only around 1.9% of households use electricity for cooking (EEPCo, 2011; CSA, 2011). EEPCo implements progressive pricing on electricity, where per-unit price increases with increased electricity usage. It is therefore obvious that this price regime discourages increased utilization of modern electric cooking appliances such as the electric mitad. We computed average price of electricity by dividing the monthly bill paid for electricity used by the amount of kilowatt hours (kwh).

The household-head variables constitute conventional variables used in previous adoption literature: age and its square, education, gender, and occupation of the household head. In this paper, we view acquisition of a major cooking appliance as an investment decision that requires a relatively substantial cash outlay by poor households.[15] Thus, we consider the decision to buy an electric mitad as a household decision and control for the characteristics of other household members residing in the same dwelling. Previous studies of technology adoption in developing countries found evidence supporting this hypothesis. Asfaw and Admassie (2004) for example, document that, in rural Ethiopia, education of other household members (in addition to heads) is a significant determinant of modern agricultural technology adoption. In view of this, we control for a broad set of household characteristics such as education, occupational structures, and access to credit by all members. Because there is strong evidence that the high startup cost and lack of access to credit prevents households in developing countries from adopting clean-energy stoves (Edwards and Langpap, 2005), we use membership in a credit association by any member of the household as a proxy for access to credit. Finally, we introduce city dummies to capture any lifestyle and other spatial differences in access to energy and information by households.

Table 1 presents summary statistics of our variables for both adopters and nonadopters of electric mitad in urban Ethiopia over the study period.[16] Clear differences in some of the main variables between adopter and nonadopter households is evident from the table. Adopter households have higher consumption expenditure, indicating better economic status than nonadopters, and on average they pay a higher average electricity price most probably indicating that the two groups fall in different price regimes. More household heads are educated in the adopter group than the nonadopter group implying the positive association of electric mitad adoption and education. One can also see differences in some of the main household-level variables. Indicating lower dependency ratio, there are less children in the adopter group than the nonadopter group, and there are more household members who are members of a credit association in the adopter group than in the nonadopter group. Adopters have a larger proportion of educated household members than nonadopter households.

Table 2 presents the percentage of the panel households adopting the electric mitads in the four cities over time. It can be noted that the proportion of electric mitad adopters is larger in the capital (Addis Ababa) than in all the other cities in all rounds. This is expected, because living in the capital could offer better access to information about modern cooking appliances. Between the years 2000 and 2009, we observe 12% 15%, 4% and 9% increases in the proportion of electric mitad adopters among

[14] Refer to Alem and Söderbom (2012) for details on computation.

[15] The average price of a standard electric mitad in urban Ethiopia and the median per capita consumption expenditure in 2009 computed from the survey in nominal prices were about $95 (1716 Ethiopian birr) and $18.80 (339.88 Ethiopian Birr) respectively.

[16] The term "adopters" refers to those households who reported that they owned and used electric mitad for baking injera in a specific wave. "Non-adopters" are those who did not own or use electric mitad.

Table 1
Descriptive statistics of variables 2000–2009.

Variables	[All households]		[Adopter households]		[Nonadopter households]	
	Mean	SD	Mean	SD	Mean	SD
Economic variables						
Real per capita cons. in birr (log)	4.728	0.760	4.983	0.695	4.477	0.737
Real price of electricity in birr (log)	−1.209	0.431	−1.238	0.438	−1.180	0.421
Real price of firewood in birr (log)	−0.476	0.800	−0.340	0.722	−0.610	0.850
Age of head	0.512	0.139	0.521	0.134	0.503	0.144
Age of head squared/100	28.124	14.740	28.942	14.285	27.321	15.135
Head female	0.461	0.499	0.411	0.492	0.510	0.500
Head educated	0.718	0.450	0.845	0.362	0.593	0.491
Head casual worker or self employed	0.318	0.466	0.229	0.420	0.406	0.491
Head formal sector employee	0.297	0.457	0.366	0.482	0.228	0.420
Household-level variables						
Number of children	1.490	1.437	1.409	1.404	1.569	1.465
Maximum female education	2.247	1.210	2.591	1.138	1.908	1.183
Member of a credit association	0.075	0.264	0.101	0.301	0.050	0.218
Member of equb	0.179	0.383	0.198	0.399	0.160	0.367
Number of casual/self-employed members	0.346	0.711	0.267	0.588	0.424	0.807
Number of formal sector employee members	0.637	0.970	0.889	1.115	0.389	0.722
Proportion of educated members	0.820	0.260	0.891	0.177	0.750	0.305
City dummies						
Addis Ababa	0.721	0.448	0.868	0.339	0.578	0.494
Awassa	0.089	0.285	0.039	0.193	0.139	0.346
Dessie	0.094	0.292	0.044	0.206	0.143	0.351
Observations	2863		1419		1444	

Table 2
Percentage of panel households adopting electric mitad over time, 2000–2009.

Cities	[2000]		[2004]		[2009]	
	Adopters	Non-adopters	Adopters	Non-adopters	Adopters	Non-Adopters
Addis Ababa (%)	58	42	56	44	70	30
Awassa (%)	17	83	17	83	32	68
Dessie (%)	19	81	27	73	23	77
Mekelle (%)	26	74	29	71	35	65
Observations	216	239	216	242	268	191

the sampled households living in Addis Ababa Awassa, Dessie and Mekelle, respectively. However, one can see from the table that the majority of households outside the capital still use biomass stoves for baking injera.

Table 3 depicts stove adoption transition of households in the sample over the study period. It can be seen that 76.03 and 82.18 percent of non-adopters and adopters, respectively, never show any transition over the study period. However, 17.82 percent of households who adopted the stove before

Table 3
Transition into and out of adoption – percentage of households.

	[Transit to]	
	Disadopter	Adopter
Disadopter	76.03	23.97
Adopter	17.82	82.18

Table 4
Determinants of electric mitad adoption: results from alternative non-linear models.

	[1-POP]		[2-REP]		[3-CREP]		[3-CME]	
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Economic variables								
Real per capita cons. in birr (log)	0.658***	0.044	0.847***	0.069	0.379***	0.098	0.080***	0.020
Real price of electricity in birr (log)	−0.357***	0.071	−0.444**	0.228	−0.454**	0.233	−0.096**	0.049
Real price of firewood in birr (log)	0.137***	0.044	0.155**	0.063	0.176***	0.065	0.037***	0.014
Age of head	0.040***	0.011	0.043**	0.017	0.049***	0.018	1.036***	0.375
Age of head squared/100	−0.023**	0.011	−0.021	0.016	−0.026	0.017	−0.006	0.003
Head female	−0.028	0.061	−0.055	0.095	−0.035	0.098	−0.008	0.021
Head educated	0.615***	0.074	0.732***	0.106	0.719***	0.108	0.152***	0.022
Head casual worker or self employed	−0.234***	0.073	−0.308***	0.108	−0.270**	0.111	−0.057***	0.023
Head formal sector employee	0.150*	0.079	0.244**	0.117	0.260**	0.121	0.055**	0.025
Household-level variables								
Number of children	0.097***	0.021	0.142***	0.032	0.160***	0.034	0.034***	0.007
Maximum female education	0.155***	0.025	0.202***	0.038	0.183***	0.039	0.039***	0.008
Member of a credit association	0.205*	0.110	0.353**	0.157	0.385**	0.161	0.082***	0.034
Member of equb	−0.020	0.074	−0.067	0.108	−0.076	0.111	−0.016	0.023
Number of casual/self-employed members	−0.179***	0.041	−0.246***	0.060	−0.220***	0.062	−0.047***	0.013
Number of formal sector employee members	0.160***	0.033	0.209***	0.048	0.209***	0.049	0.044***	0.01
Proportion of educated members	0.557***	0.137	0.830***	0.203	0.826***	0.209	0.175***	0.043
City and Time Variables								
Addis Ababa	0.827***	0.102	1.277***	0.180	1.382***	0.189	0.293***	0.036
Awassa	−0.627***	0.140	−0.809***	0.235	−0.859***	0.244	−0.182***	0.051
Dessie	−0.213	0.135	−0.334	0.227	−0.293	0.235	−0.062	0.050
2004	–	–	0.039	0.086	0.074	0.088	0.016	0.019
2009	–	–	0.096	0.239	0.179	0.245	0.038	0.052
Intercept	−6.832***	0.429	−8.884***	0.708	−10.817***	0.849	–	–
Pseudo *R*-squared	0.307	–	–	–	–	–	–	–
Rho	–	–	0.536***	0.043	0.557***	0.043	–	–
Log-likelihood	−1376.169		−1313.498		−1291.231	–	–	
Observations	2863		2863		2863		2863	

POP: is the pooled probit estimator. REP: is the random effects probit estimator. CREP: is the correlated random effects probit model. CME: shows the marginal effects from the CREP.
Significance at the 1%, 5%, 10% level is indicated by ***, **, *, respectively.

2009 become non-adopters,[17] and 23.97 percent of the non-adopters transition to electric stoves in 2009. This makes the analysis of what determines transition important.

5. Empirical results

5.1. Adoption of electric mitad appliance

Table 4 shows regression results and the corresponding marginal effects for the determinants of electric mitad adoption as presented in Eq. (1). As stated in the preceding section, we examine the correlates of electric mitad appliance adoption under four headings: economic variables, household head's characteristics, household-level variables, and city and time dummies. To test for the robustness of the different correlates of adoption, we estimate the model using three alternative nonlinear specifications: pooled probit, random effects probit and correlated random-effects probit models. Comparison of results in Table 4 reveals that our regressions from all the estimators provide similar

[17] In effect, these households are "dis-adopters" who stopped using the cookstove.

results in terms of signs of the relevant coefficients, indicating the robustness of our findings. However, the pooled probit estimator, which does not control for time-invariant unobserved heterogeneity, underestimates most of the coefficients. The coefficient for *rho*, which indicates the important role of unobserved heterogeneity, is significantly different from zero and is large in magnitude in both the random effects and correlated random-effects probit models (0.53 and 0.55, respectively). This clearly indicates the need to use panel data models in estimating the cookstove adoption model. Because the correlated random-effects probit model is based on an appealing formulation that allows for correlation between some of the explanatory variables and the unobserved individual heterogeneity term, we refer to the results from this estimator in our discussion below.

It is evident from all the regression results that most of the economic, household head, household-level, and city-level variables are important in explaining adoption of electric mitad appliances in urban Ethiopia. We begin with economic variables. One can see from Table 4 that the economic status of the households as measured by per capita consumption expenditure is a positive and significant determinant of adoption of an electric mitad appliance. This is consistent with findings from earlier studies (e.g., Amacher et al., 1992; Arthur et al., 2010; Beyene and Koch, 2012; Gebreegziabher et al., 2012; Jan, 2012), who document the importance of economic status in explaining adoption of modern cookstoves. An increase in the price of electricity reduces adoption of electric mitads and an increase in the price of the substitute fuel (firewood) increases adoption. The marginal effects presented in column 4 indicate that, other factors held constant, a one percent increase in the price of electricity reduces adoption by 9.6 percent, and a one percent increase in the price of firewood increases adoption by 3.7 percent. This indicates the role that, for instance, reduction in the price of electricity (say through subsidy) and increase in the price of firewood (through tax) could play in encouraging households to switch to cleaner energy sources.

We further explore the impact of the price of electricity by testing the null hypothesis that adopters and non-adopters fall in the same electricity price regime. Using a simple two-sample mean comparison test, we specifically test whether the two groups of households fall under the same blocks of price of electricity. We rejected the null hypothesis (p-value 0.000) that adopters and non-adopters have the same mean prices or fall under similar blocks of electricity prices. This finding most probably indicates that any intervention which results in reduction in the average price of electricity would encourage non-adopters to adopt the electric mitad and reduce the consumption of biomass energy sources.

Consistent with earlier findings, household heads' characteristics are important correlates of modern cookstove adoption. Households with heads who are aged, educated and working in the formal sector are correlated positively with adoption of electric mitad appliances, while those with heads working as self-employed and casual workers are not. Earlier studies (e.g., Beyene and Koch) find differences in adoption based on gender of the household head. We do not find a gender difference in adoption, as can be seen from the insignificant coefficient on the "Female" variable. The sign is, however, negative, implying that female headed households are less likely to adopt electric mitads. Detailed investigation of the difference sections of our panel data indicates that about 32.02 percent of the female headed households in urban Ethiopia engage in small-scale, traditionally female business activities, such as preparing and selling food and drinks. Thus, they appear to have a lower tendency to adopt an electric mitad appliance for a number of possible reasons, such as low opportunity cost of time, which could be used to collect and buy traditional biomass fuel.

Because of our interest in the role of other household members in making the decision to adopt an electric mitad, we control for the educational and occupational characteristics of other household members. All the three nonlinear models presented in Table 4 suggest that, in addition to household heads' characteristics, other household members' educational and occupational characteristics have a significant effect on the adoption of electric mitads. Consistent with our discussion above, households with more members earning a living as self-employed or casual workers have a lower likelihood of adopting electric mitads, while those with more members working in the formal sector have a higher likelihood. Our results show that maximum female education and a larger proportion of educated household members are positively associated with adoption of electric mitads, most probably indicating the positive spill-over effects of education in the household. We also note that households with a larger number of children are more likely to invest in electric mitads. This is probably due to awareness on the adverse consequences to the health of children of using biomass energy.

Because acquisition of modern cooking appliances is constrained by lack of access to credit (Edwards and Langpap, 2005), we control for access to credit and for savings by any household member by using membership in credit associations and "equbs" as proxies.[18] The results in Table 4 suggest that access to credit by any member of the household positively affects the ability to purchase and adopt electric mitads. The reported marginal effects indicate that membership in a credit association by any member of the household increases the probability of adoption by 8.2 percent. This reinforces earlier findings on the importance of access to financial resources in enabling households to adopt improved cookstoves and make a transition to cleaner energy sources. We do not find access to a traditional savings institution (equb) to be a significant factor. This most probably indicates that, in a developing country setting such as urban Ethiopia, access to credit is more important than access to saving for acquisition of modern electricity cooking appliances.

Finally, the coefficients on the city dummies indicate a clear spatial difference in adoption of electric mitads, with strongly statistically significant coefficient estimates. Compared to households in the reference city, Mekelle, households in the capital Addis are more likely to adopt electric mitads, while households in the city of Awassa are less likely to adopt. Households living in the capital have about a 29.3% higher probability of adopting electric mitads compared to households in Mekelle. On the other hand, households in the city of Awassa have about a 18.2% lower probability of using an electric mitad. This could probably be explained by better biomass fuel availability and the relatively lower level of awareness about the implications of using biomass fuel in the city of Awassa (Reynolds et al., 2010).

5.2. *Transitions into and out of adoption*

In order to answer the question "which households adopt and disadopt electric mitad appliance over time in urban Ethiopia?" we use discrete–time hazard models on the balanced panel of 446 households observed over the entire period of time and estimate two hazard functions: one for entry into and another for exit from electric mitad adoption.[19] To check for the robustness of the impact of the different variables on the hazards of entry into and exit from adoption, we estimated the models using both non-proportional and proportional hazard models.[20] The regression results presented in Table 5 reveal no significant difference between the non-proportional and proportional hazard models. Both models are estimated with unobserved household heterogeneity.

The results in columns [1] and [3] of Table 5 suggest that, controlling for city and time fixed effects, the transition from the state of no adoption to adoption of electric mitad is strongly determined by the price of electricity (negative) and the price of firewood (positive). This is consistent with findings from the correlated random effects probit model and implies that an increase in the price of electricity and decrease in the price of firewood over time may hinder households from moving from not adopting to adopting an electric mitad. We do not find per capita consumption expenditure as an important determinant of entry into adoption in the proportional hazard model.[21] Consistent with results from the model of adoption, households with educated heads are more likely to enter into adoption. None of the other household head related variables are important in explaining the hazard of entering into adoption. Results also confirm the importance of household-level variables in entering into adoption. The number of children, maximum female education, access to credit by any member of the household, the number of household members employed in the formal sector, and proportion of educated members all positively determine transition into adoption.

[18] Equbs are informal Rotating Saving and Credit Associations commonly used by households in urban Ethiopia. See Kedir et al. (2005) for definitions and institutional arrangement of equbs.

[19] Our dependent variable has been constructed from the response to the question regarding ownership of an electric mitad. We acknowledge the role that reporting errors might have played, as would be the case in many survey data sets collected in developing countries.

[20] We estimated the non-proportional hazard model using the logit specification, which is a widely used discrete–time non-proportional hazard model (Jenkins, 1995).

[21] The variable is slightly significant (10%) in the non-proportional hazard model.

Table 5
Entry into and exit from electric mitad adoption: results from proportional hazard models.

	[1-ENNPH]		[2-EXNPH]		[3-ENPH]		[4-EXPH]	
	Coef.	SE	Coef.	SE	Coef.	SE	Coef.	SE
Economic variables								
Real per capita cons. in birr (log)	0.169*	0.110	−1.589***	0.417	0.116	0.086	−1.319***	0.315
Real price of electricity in birr (log)	−1.028***	0.227	0.879***	0.351	−0.764***	0.157	0.793***	0.281
Real price of firewood in birr (log)	0.510***	0.110	0.078	0.248	0.389***	0.089	0.043	0.209
Age of head	3.533	3.229	−1.636	7.983	3.151	2.506	−1.301	6.753
Age of head squared/100	−2.348	3.045	−1.875	7.379	−2.359	2.362	−1.540	6.230
Head female	0.255*	0.159	−0.229	0.423	0.186	0.124	−0.194	0.356
Head educated	1.160***	0.185	−4.332***	1.070	0.940***	0.153	−3.862***	0.842
Head casual worker or self employed	−0.161	0.201	−0.310	0.451	−0.118	0.158	−0.317	0.379
Head formal sector employee	−0.024	0.184	−0.986*	0.548	−0.034	0.138	−0.889**	0.466
Household-level Variables								
Number of children	0.090	0.058	−0.355*	0.193	0.073*	0.044	−0.306**	0.155
Maximum female education	0.128*	0.070	−0.065	0.159	0.130**	0.058	−0.057	0.134
Member of a credit association	1.345***	0.181	−1.676	1.127	0.971***	0.129	−1.472	0.956
Member of equb	0.080	0.189	1.048*	0.591	0.034	0.144	0.850*	0.485
Number of casual/self-employed members	−0.066	0.108	−0.243	0.254	−0.051	0.085	−0.215	0.206
Number of formal sector employee members	0.182***	0.069	−0.942***	0.329	0.106**	0.052	−0.856***	0.280
Proportion of educated members	1.255***	0.403	−1.745**	0.825	0.983***	0.334	−1.488**	0.644
City and Time Variables								
Addis Ababa	0.480*	0.294	0.440	0.737	0.491**	0.247	0.367	0.621
Awassa	−0.669*	0.407	0.280	1.027	−0.432	0.343	0.315	0.876
Dessie	0.178	0.406	−0.525	0.954	0.180	0.355	−0.419	0.815
2009	−1.531***	0.277	0.782	0.536	−1.158***	0.205	0.793*	0.443
Intercept	−6.821***	1.143	8.841***	3.124	−5.859***	0.889	6.952***	2.453
Log-likelihood	−576.369		−157.865		−578.489		−157.254	
Observations	1340		1340		1340		1340	

EN-NPH: Entry into adoption – Non-proportional hazard model. EX-NPH: Exit from adoption – non-proportional hazard model.
EN-PH: Entry into adoption – proportional hazard model. EX-PH: Exit from adoption – proportional hazard model.
Significance at the 1%, 5%, 10% level is indicated by ***, **, *, respectively.

Columns [2] and [4] of Table 5 present discrete–time non-proportional and proportional hazard estimation results, respectively, for exiting the state of adoption over time. The results suggest that economic status as measured by per capita consumption expenditure has a negative impact on the hazard of exit from adoption. This is consistent and intuitive, given the fact that households, all other factors remaining constant, may decide to discontinue using the appliance and move to a biomass-using stove as their economic conditions worsen. The price of electricity, on the other hand, has a significant positive effect on the hazard of exit from adoption. We do not find a statistically significant effect of the price of firewood on exit from adoption of the electric mitad. This could be due to the fact that, once households have started adopting the electric mitad, a change in the price of firewood (say a decrease) would not give them the incentive to switch into biomass-using stoves, because using a biomass stove imposes other costs on the household, such as health hazards from smoke. Finally, one can see from columns [2] and [4] that most of the significant household head and household-level variables display effects on the hazard of exit that are the opposite of their effects on the hazard of entry.

6. Conclusions and policy implications

This paper, probably the first to use panel data in a study of clean-energy stove adoption in developing countries, investigates the determinants of adoption and disadoption of an electric cooking appliance – the mitad – in urban Ethiopia. In order to combat the adverse consequences of biomass fuel use, such as deforestation, indoor air pollution and emission of greenhouse gasses in developing countries, reducing the intensity of biomass fuel use and transitioning to cleaner energy sources is an important step. However, as documented in previous studies, such a transition is conditioned by adoption of improved cookstoves. For this reason, our analysis of the determinants of adoption and disadoption of improved cookstoves that use clean energy provides useful information to policy makers. The three rounds of panel data at hand enabled us to control for unobserved household heterogeneity and investigate adoption and disadoption of the appliance by households over time.

We find that adoption of electric mitad appliances in urban Ethiopia is strongly determined by economic status, price of electricity and price of firewood (the alternative fuel). We also show that access to credit and socio-economic characteristics of not only household heads but also other household members are important determinants of adoption. For instance, marginal effects from a correlated random-effects probit model show that, compared to households headed by an uneducated individual, households with a head who completed at least primary education have a 15.2 percent higher probability of adopting an electric mitad appliance. However, not only the education of the head matters, but also that of other household members. A one percent increase in educated household members increases the likelihood of adopting an electric mitad by 17.5 percent. This reinforces our hypothesis that the decision to acquire a modern cooking appliance may depend on a broader set of household-level characteristics.

We also investigated the likelihood of entering into and exiting from adoption by households in urban Ethiopia using hazard analysis. Economic status (positive), price of electricity (negative), and price of firewood (positive) determine the likelihood of transition from the state of adoption to non-adoption. Socio-economic characteristics of all household members and access to credit have also been found to be important determinants of such transitions. Most of the explanatory variables that positively determine transition of households into adoption negatively determine transition out of adoption, with the exception of the price of firewood, which positively determines entry into adoption but has no statistically significant effect on exit from adoption. This could possibly be due to the fact that, once households invest in the appliance and develop a taste for using it, reduction in the price of firewood alone may not be a sufficient condition to make them exit from adoption.

We argue that the use of robust non-linear panel data econometric tools on data spanning a fairly long period of time adds useful insights to the growing literature on clean-energy cookstove adoption in developing countries. Our findings that prices of electricity and firewood are important determinants of adoption and dis-adoption support the idea that raising the price of biomass fuel (for example, by introducing a tax) and reducing the price of electricity (for example, through a carefully-designed subsidy or reduction in the average price of electricity through investment in hydroelectric power production) would have a positive impact on adoption. This could be more effective if combined with interventions that improve access to credit, such as micro-finance supports, as the urban poor lack the financial capacity to meet the start-up cost of acquiring modern cooking appliances. In addition, the fact that the socio-economic characteristics of other household members are also important determinants of adoption indicates the trickle-down effects of factors such as education and labor market status within the household. This could be important information for policy makers and stakeholders such as NGOs that aim to promote the adoption of modern cookstoves and the reduction of the pressures on forest resources by households in developing countries.

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