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Essays on the impact on households
of natural resource scarcity and
climate change

BAHRE GEBRU KIROS

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Bahre Gebru Kiros

Faculty of Natural Resources and Agricultural Sciences

Department of Economics

Uppsala



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© 2023 Bahre Gebru Kiros, <https://orcid.org/0000-0002-9438-5495>

Swedish University of Agricultural Sciences, Department of Economics, Uppsala, Sweden

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Abstract

This thesis comprises four empirical papers aimed at comprehending the interdependencies among climate change, scarcity of natural resources such as water and forests, human health, and households' responses.

Paper I investigates the impact of precipitation variability on households' sanitation technology choices in Ethiopia. The findings indicate that increased precipitation variability causes households to abandon improved sanitation facilities in favor of unimproved sanitation systems. Paper II examines how local forest resource conditions affect households' fuel choice in Uganda. The use of biobased fuels has detrimental effects on both human health and forests. The results show that, when compared to households in non-vegetated areas, those in more vegetated areas are less likely to depend on dirty biobased fuels like firewood and charcoal. A larger forest stock is associated with a greater likelihood of using a combination of clean and dirty fuels. Paper III analyzes the impacts of water scarcity, as measured by time spent collecting water, on diarrhea prevalence and the purchase of health insurance in Ethiopia. Results show that water scarcity has a significant and positive impact on both. Finally, paper IV scrutinizes the effects of seasonal temperature on seasonal farm labor market outcomes in Ethiopia. The main findings show that rising temperatures reduce the number of hired farm labor days and wage payments during planting, harvesting, and whole agricultural season.

Keywords: Climate change, diarrhea, Ethiopia, farm labor market, forests, fuel choice, health insurance, natural resource scarcity, sanitation facilities, Uganda.

Dedication

This thesis is dedicated to my parents, Gebru Kiros and Akeza Abay, and my father-in-law, Abraha Belayneh. I also dedicate it to the children, young girls, and women in the war-torn Tigray and Maria Hernandez, a humanitarian who was murdered there.

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List of publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

- I. Gebru, B.*, Elofsson, K., Amuakwa-Mensah, F. and Marbuah, G. (2023). Climate variability and its impact on sanitation facility choice: evidence from Ethiopia. [Manuscript]
- II. Gebru, B.* and Elofsson, K. (2023). The role of forest status in households' fuel choice in Uganda. *Energy Policy*, 173. Published online, and forthcoming in print.
- III. Gebru, B.* and Elofsson, K. (2023). The impacts of water scarcity on health outcomes: an instrumental variables approach. [Submitted]
- IV. Gebru, B. (2023). The effects of temperature on farm labor market outcomes in Ethiopia. [Manuscript]

* Corresponding author.

Paper II is reproduced with the permission of the publisher.

The contribution of Bahre Gebru Kiros to the papers included in this thesis was as follows:

- I. I formulated the problem and research questions together with my supervisors. I conducted the data curation and analysis, and prepared the initial draft. I wrote the final version with support from the co-authors.
- II. I formulated the problem and research question, conducted the data curation and analysis, and prepared the initial draft. I wrote the final version together with my co-author.
- III. I formulated the problem and research question, conducted the data curation and analysis, and prepared the initial draft. I wrote the final version together with my co-author.
- IV. I formulated the problem and research question, conducted the data curation and analysis, and prepared the initial draft. I wrote the final version with feedback from the main supervisor.

1. Introduction

Climate change and natural resource scarcity influence household decisions, prompting adaptations in sanitation and health, fuel usage, and labor allocations. This doctoral thesis attempts to understand the effects of climate change and natural resource scarcity (specifically water and forests) on household decision making in the context of Ethiopia and Uganda. The relationship between climate change and natural resources scarcity is outlined in section 1.1. The following section 1.2 discusses households' responses to climate change and accompanying resource scarcity. Section 1.3 identifies the knowledge gaps. The purpose of the thesis is presented in section 1.4. The research questions addressed in each paper are provided in section 1.5. The last section of the introduction outlines the structure of the thesis.

1.1 Climate change and natural resource scarcity

Climate change adversely affects natural resources such as water and forests. Climate change leads to a rise in global temperatures and alters the frequency and intensity of precipitation (Solomon et al., 2007; Batisani and Yarnal, 2010; Maenza et al., 2017). Consequently, there will be changes in water supplies and occurrences of floods, posing a threat to the availability of and quality of water (Brown and Lall, 2006; Gosain et al., 2006; Koubi et al., 2012; Misra, 2014; Howard et al., 2016). Therefore, it is predicted

that climate change will worsen the problems of water scarcity in the 21st century (Connor et al., 2012; Jaeger et al., 2017).

Climate change will also have an impact on forests. Both direct and indirect effects of climate change on forests are possible. For example, tree deaths can be a direct result of global warming, water scarcity, insect infestations, forest fires, and diseases (Daniels et al., 2011; Seidl et al., 2017). Climate change indirectly poses detrimental effects on forests by contributing to the persistence of household poverty. Households find it harder to accumulate assets and regularly deplete their stock of assets as a result (Dercon, 2004; Krishna, 2006). This might encourage them to get involved in the collection and sale of firewood from forests to improve their well-being and meet their energy needs (Cavendish, 2000). The production of firewood and charcoal is the main reason for forest degradation in Africa (Kissinger *et al.*, 2012). Climate change has also the potential to increase the reliance of households on forests as a source of income from timber (Fisher and Shively, 2005; Kamanga et al., 2009). The use of wood from forests has a negative effect on the overall functioning of forest ecosystems (Herington *et al.*, 2016; Shankar *et al.*, 2020). In general, climate change may increase the opportunity cost of resource extraction, worsening resource scarcity. Fig. 1 presents an overview of these connections. The subsequent subsection delves into a discussion of the decisions made by households in addressing these challenges.

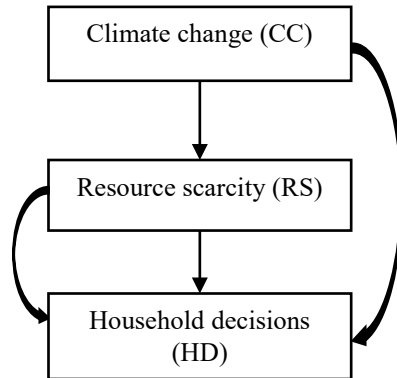


Fig. 1. The links: climate change, resource scarcity, and household decisions.

1.2 Household responses and their implications

Climate change impacts households' decision-making both directly and indirectly by creating resource scarcity as seen in Fig. 1. Households make economic decisions in response to these impacts. These decisions have far-reaching implications, affecting various aspects of households' lives. Households may experience increased competition from other resource users as resources become scarcer. This might intensify conflicts over access to limited resources (Almer et al., 2017; Yousef, 2021; Unfried et al., 2022). Based on quality of the resource, cost of extraction, and accessibility conditions, households decide where, how, when, and how much to use (Robinson *et al.*, 2008).

Households respond to resource scarcity by spending more time gathering water and firewood. When there is a lack of water, household members, especially women and children, may have to travel further or wait longer in queues to get water (Boone et al., 2011; Meeks, 2017; Gross et al., 2018). Households who live further from the forest also spend more time gathering fuelwood. These households will probably buy less

fuelwood and sell more of it (Bošković *et al.*, 2023). The amount of time spent on collecting natural resources has significant implications for households. Resource gathering poses challenges for children's development and restricts their available time for educational activities (Beegle *et al.*, 2009; Choudhuri and Desai, 2021). Gathering resources has an effect on the labor market, showing that using more biomass energy is negatively associated with female labor market participation (Burke and Dundas, 2015).

There are health risks associated with the collection and use of natural resources. Individuals who collect them often face physical strain, safety risks, and gender-based violence during their journeys to gather these resources. The likelihood of resorting to unprotected water sources, such as surface sources, dug wells, and springs, for water collection may rise due to climate change-induced water scarcity. This situation could increase the risk of diarrhea due to poor water quality. Households could also make decisions in terms of their sanitation facilities in response to higher precipitation variability. There is a trade-off between improved and unimproved sanitation facilities. The former includes flush toilets, ventilated pit latrines, pit latrines with slabs, and composting toilets. The latter comprises pit latrines without slabs, buckets, and open defecation. The improved sanitation infrastructure has an advantage over the latter due to their ability to distinguish between human contact and excrement. These facilities, being exclusive to a particular household, provide advantages in terms of privacy, hygiene, health, convenience, and accessibility (UNICEF and WHO, 2019). Water-efficient sanitation technologies, like low-flush toilets, may be more appropriate in households with limited water supplies to reduce water consumption. However, during severe weather events that

might potentially harm the sanitation and water infrastructures, flood-resistant sanitation facilities might be given priority.

Households who choose unimproved facilities run the risk of contracting diarrheal diseases due to poor sanitation practices. Climate change-related issues have significant health and economic consequences. Several studies, including Karlsson and Ziebarth (2018), Yu et al. (2019), and Agarwal et al. (2021), have shown a connection between temperature rises and an increase in hospital admissions and deaths. This might lead to missed work (Somanathan et al., 2021; Heyes and Saberian, 2022), lower productivity (Amacher et al., 2004; Burke et al., 2015; Chen and Gong, 2021), and adverse income consequences (Amacher et al., 2004). Health insurance could have the potential to offer households improved access to medical care, encompassing the diagnosis and treatment of health issues linked to climate change and water scarcity.

The decision to use dirty energy sources like firewood, charcoal, crop residues, and animal dung may also have detrimental health effects. These biofuels cause air pollution (Smith, 2000; Muller and Yan, 2018), respiratory illnesses (Edwards and Langpap, 2012; Jagger and Shively, 2014), and cardiovascular diseases (Adhvaryu *et al.*, 2023). In addition to harming one's health, using dirty fuels also damages the environment (Acemoglu *et al.*, 2012; Manning and Taylor, 2014). Fuel-based health problems have similar economic implications to water-related health risks. So how do households deal with these challenges?

The increasing scarcity of natural resources poses a serious threat to the populations whose livelihoods depend on the resources (Leone, 2019). Sustainable management of common pool resources has become a crucial current issue due to rural households' dependence on natural resources and the public nature of environmental goods (Adhikari et al., 2004). Switching

to clean fuels like kerosene, LPG, solar energy, and electricity could be one way to combat the growing negative welfare effects of using biofuels (Smith, 2002; Lee, 2013). That might be advantageous for both households and the environment (Stern, 2010; Garland *et al.*, 2015). But what actually happens in practice is so called fuel stacking, in which households mix various fuels (Pillarisetti *et al.*, 2019; Troncoso *et al.*, 2019). The households view the use of mixed fuels as a risk-reduction strategy because clean fuels are frequently expensive and have unpredictable supplies. Cultural norms and behavioral factors may also contribute to fuel stacking. Instead of anticipating a complete switch to clean fuels, the focus could instead be on using mixed fuels in the short term.

Climate change has also wide-ranging effects on labor markets. Rural households shift their family labor from on-farm work to off-farm work during unfavorable weather (Ito and Kurosaki, 2009; Huang *et al.*, 2020). Higher temperatures affect agricultural operations by interfering with planting and harvesting schedules. The impact on labor allocation goes beyond own household labor. Higher temperatures have a detrimental effect on agricultural productivity by reducing crop production. This might directly impact external agricultural labor, such as hired labor and free labor obtained through social networks, and the associated wage payments. Higher temperatures can disrupt social networks by reducing opportunities for generating income and may change social ties. The time allocated for gathering natural resources and the loss of labor days (and thus income) due to illnesses associated with climate change and using biofuels could also impact farm labor markets. This has the potential to affect households' available time for agricultural activities. Due to resource scarcity and climate change, households may thus be forced to move to areas with better resource availability, further affecting labor allocations.

In the agricultural sector, higher temperatures can create a trade-off in farm inputs, with effects on labor allocation decisions. Higher temperatures lead to increased presence of weeds, pests, and crop diseases. Farm managers often increase the use of defensive inputs, such as pesticides, to address these challenges. This decision might reduce the need for labor in weed control. Farmers might opt to reduce the utilization of productivity-enhancing inputs such as fertilizers due to liquidity constraints (Jagnani et al., 2021). The adverse effects of higher temperatures on plant growth further contribute to the decreased application of fertilizers.

1.3 Knowledge gaps

In light of the above, this doctoral thesis comprises four empirical research papers that investigate the role of climate change and natural resource scarcity on household decision-making in Ethiopia and Uganda. Although there have been qualitative reports, the attention given to the impact of climate change on sanitation choice has been limited (Howard and Bartram, 2010; Howard *et al.*, 2016; Dickin *et al.*, 2020). The first paper addresses this research gap by presenting empirical evidence that examines the connection between precipitation variability and the selection of sanitation facilities in Ethiopia. It analyzes the direct link between climate change and household decisions shown in Fig.1.

There is limited evidence regarding the interconnections among forest degradation, firewood collection, and fuel choice (Heltberg *et al.*, 2000; Pattanayak *et al.*, 2004). Only a small number of studies have investigated the relationship between firewood scarcity and fuel choice, with the majority relying on self-reported measures such as the time spent collecting firewood or distance to the forest source. The second paper fills the existing research gap by investigating the role of local forest stock conditions on

fuel choice among households in Uganda. The study employs Enhanced Vegetation Index (EVI) as an indicator to assess forest availability and biomass richness to overcome concerns regarding measurement errors. This paper explores the link from resource scarcity to household decisions highlighted in Fig.1.

In economics, certain studies have analyzed the impact of water scarcity and the provision of piped water on specific health outcomes, such as infant mortality rates (Gamper-Rabindran *et al.*, 2010; Rocha and Soares, 2015). Nevertheless, none of these studies have specifically investigated the effect on the prevalence of diarrheal diseases, despite its significant health implications. Furthermore, it remains unclear whether individuals react to the rise in water scarcity by acquiring health insurance. The third paper fills the gap in knowledge by investigating the effects of water scarcity on the prevalence of diarrhea and purchase of health insurance. This paper investigates two links presented in Fig. 1: the relationship between climate change and resource scarcity, and the association between resource scarcity and household decisions.

High temperatures have been found to have a negative impact on labor supply and demand, with studies indicating decreased productivity and increased fatigue. Farm managers have the option to meet their labor requirements by utilizing family labor, hired labor, and accessing free labor through social networks. However, the sensitivity of these labor sources to rising temperatures has not received much attention in the literature. The final paper therefore examines the relationship between temperature and farm labor market outcomes in Ethiopia. The paper specifically investigates the link from climate change to household decisions, which is elucidated in Fig. 1. While the first, second, and fourth papers use households as the main unit of analysis, the third paper primarily focuses on individual-level

analysis. With the exception of paper II, all of the papers discuss potential mechanisms that could help to explain the key findings. Table 1 presents the titles of papers associated with the thesis, focusing on the specific links provided in Fig. 1 and the corresponding country of study.

Table 1. The papers, links addressed, and study context.

Paper	Title	Links addressed	Focus country
I	Climate variability and its impact on sanitation facility choice: evidence from Ethiopia	CC→HD	Ethiopia
II	The role of forest status in households' fuel choice in Uganda	RS→HD	Uganda
III	The impacts of water scarcity on health outcomes: an instrumental variables approach	CC→RS and RS→HD	Ethiopia
IV	The effects of temperature on farm labor market outcomes in Ethiopia	CC→HD	Ethiopia

Note: Table 1 provides an overview of the paper titles and indicates whether each paper investigates the effect of climate change, natural resource scarcity, or their combined effects on household decisions. It also includes information about the geographical context of the studies. The acronym CC→RS denotes the impact of climate change leading to resource scarcity. RS→HD represents the connection between resource scarcity and household decisions. The influence of climate change on household decisions is shown by CC→HD.

1.4 Purpose of the thesis

The purpose of this thesis is to examine the impact of climate change and the scarcity of natural resources, specifically water and firewood, on households' economic decisions. The thesis explores the effects of climate change in relation to the scarcity of natural resources and the decisions made by households. These decisions include the selection of sanitation facilities, fuel sources, the purchase of health insurance, as well as the allocation of farm labor and the corresponding wage payments.

1.5 Research questions

Each paper within the thesis focuses on a particular research question derived from the identified knowledge gaps in section 1.3. Table 2 provides a summary of the specific research questions associated with each individual paper.

Table 2. The papers and associated research questions.

Paper	Research question
I	What impact does higher precipitation variability have on the choice of improved and unimproved sanitation systems?
II	Do households living in better forest areas rely more on biobased dirty fuels, specifically firewood and charcoal?
III	What is the relationship between water scarcity and the incidence of diarrheal infections and the possession of health insurance?
IV	What is the impact of rising temperatures on seasonal allocation of farm labor and corresponding wage payments among family labor, hired labor, and free labor from social networks?

Note: Table 2 presents an overview of the research questions that are explored in each paper.

1.6 Structure of the thesis

The remaining sections of the thesis are structured as follows: Section 2 describes the data sources and analysis techniques. Section 3 summarizes the appended papers. Section 4 mentions the contribution of the thesis, discusses the implications for policy, and identifies future research areas.

2. Data and methods

This section discusses the data sources and analytical techniques applied in the thesis. It starts off by describing the data sources before moving on to the analysis techniques.

2.1 Data sources

The thesis relies on three large data categories: household surveys, weather data, and water quality test data. Each data category and its related papers are covered in more detail in the following subsection.

2.1.1 Household survey data

The first source of data used in the thesis are household surveys. The World Bank's Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA) provides these data to the studies in Ethiopia and Uganda. The Ethiopia Socioeconomic Survey (ESS) is conducted in 2011/12, 2013/14, and 2015/16. The household survey in Ethiopia is used in papers I, III, and IV. However, there are some differences between the papers in terms of the survey periods considered. Papers I and IV use all three survey periods. Paper III exclusively focuses on the second and third survey periods when examining the occurrence of diarrhea. This is due to the fact that these surveys consider both urban and rural areas and employ a

two-week timeframe to assess the prevalence of diarrhea. In contrast, the initial survey period excludes urban areas and utilizes a two-month period preceding the survey as the window for measuring diarrhea prevalence. This longer timeframe is more susceptible to measurement errors. The analysis of the decision to purchase health insurance focuses solely on data from the third survey period, as the information related to insurance is available exclusively during that period. The ESS data are extensively used in previous research. He and Chen (2022), Abay et al. (2021a), and Abay et al. (2021b) are a few examples. Turning to Uganda, the Uganda National Panel Survey (UNPS) was carried out in 2009/10, 2010/11, and 2011/12. These data serve as the basis for the analysis conducted in paper II. Earlier studies have also utilized these data sources, e.g., Ali *et al.* (2016), Tesfaye and Tirivayi (2020), and Antonelli *et al.* (2022).

2.1.2 Weather data

Weather data are the second category of data used in the doctoral thesis. These data include monthly minimum and maximum temperatures in °C and precipitation in mm. They are extracted from the Climatic Research Unit of the University of East Anglia (CRU-UEA) (Harris et al., 2014). The weather data from CRU-UEA are of high quality (Mitchell and Jones, 2005) and are widely used in the literature (Mitchell and Jones, 2005; Freudenreich et al., 2022).

These weather data are utilized in papers I, III, and IV, although there are some notable differences. The first distinction is in terms of temporal scale. The weather data in papers I and III consider 30 years of data preceding each household survey period. Paper IV only uses weather data from 2011/12 to 2015/16, which corresponds to the household survey periods in that paper. The weather variable of interest also differs between

the papers. In this regard, paper I focuses on precipitation variability, paper III on temperature shocks, and paper IV on temperature levels. The third difference is in the definition of temperature levels. Papers I and III define average annual temperatures by taking the averages of average annual minimum and maximum temperatures. This is so because water sources and sanitation facilities are inherently susceptible to temperature fluctuations, making the use of average temperature measurements logical. The analysis in paper IV, however, is based on monthly maximum temperatures for two main reasons. Firstly, farm laborers spend some time indoors, especially during activities like sleeping when minimum temperatures occur. Secondly, maximum temperature is highly correlated with other relevant temperature measurements. Therefore, monthly maximum temperature is deemed a reasonable proxy for individual temperature exposure (Graff Zivin and Neidell, 2014).

2.1.3 Water quality test data

The water quality test (WQT) data are the final category of data used in the thesis. These data are utilized to examine the connection between temperature shocks and the risk for *Escherichia coli* contamination. They are also used to explore the relationship between temperature shocks and fluoride content, water hardness, and electroconductivity as key indicators of water quality. In a nutshell, Table 3 provides the summary of the various data sources used in the thesis.

Table 3. Data sources used in the papers.

Paper	Data	Source	Survey periods /weather years
I	Household survey:		
	LSMS-ISA	ESS	Surveys I, II, and III
	Weather data	Precipitation and temperatures (minimum and maximum)	1981-2014
II	Household survey:		
	LSMS-ISA	UNPS	Surveys I, II, and III
III	Household survey:		
	LSMS-ISA	ESS	Surveys II and III
	Weather data	Precipitation and temperatures (minimum and maximum)	1983-2014
	WQT data	ESS	Survey III
IV	Household survey:		
	LSMS-ISA	ESS	Surveys I, II, and III
	Weather data	Maximum temperatures and precipitation	2011-2015

Note: Table 3 provides an overview of the different data categories utilized in each paper. It also contains their respective sources, survey periods, and the corresponding years of weather data.

2.2 Methods

The papers use a variety of analyses methods, which are listed in Table 4. Paper I employs a panel fixed-effects approach to account for unobserved heterogeneity and eliminate time-invariant characteristics that may confound estimates in sanitation facility choice. This paper uses Heckman fixed-effects two-step estimator to tackle possible selection bias in water investment. The placebo tests are used to demonstrate that the impact of

precipitation variability is restricted to using piped water specifically during the rainy season. The multinomial logit model (MNL) is used to model households' choice among multiple sanitation alternatives, such as private improved, shared improved, and unimproved sanitation facilities. The second paper uses the random-effects multinomial logit model fitted with generalized structural equation modeling (REMNL-GSEM). This method tackles unobserved heterogeneity by allowing a correlation among the residuals of the clean, dirty, and mixed fuel equations within a given household, while not extending this correlation across households. The analysis extends to random-effect probit models (REPM) and linear probability models (LPM) as a robustness exercise.

An instrumental variable, a two-stage least squares (IV/2SLS) estimation method along a set of falsification tests are used in the third paper. The IV approach is employed to mitigate potential endogeneity issues arising from measurement errors in water scarcity. The fourth paper employs a Poisson Pseudo-Maximum Likelihood regression with a high-dimensional fixed-effects model (PPML-HDFEM) and falsification tests. This method is applicable to non-negative dependent variables and does not require explicitly specifying a distributional assumption for them. Moreover, it provides a natural way to handle zero values in the dependent variables.

Table 4. Methods of analysis used in the papers.

Paper	Main analysis	Robustness checks
I	Panel fixed-effects, Heckman fixed-effects two-step estimator, placebo tests	Panel fixed-effects and MNLM
II	REMNLN-GSEM	REMNLN-GSEM, REPM and LPM
III	IV/2SLS with falsification tests	IV/2SLS and falsification tests
IV	PPML-HDFEM and falsification tests	PPML-HDFEM and falsification tests

Note: Table 4 shows a summary of the econometric methods and falsification tests that are covered in the papers.

3. Summary of appended papers

This section summarizes the four papers included in the doctoral thesis.

3.1 Paper I: Climate variability and its impact on sanitation facility choice: evidence from Ethiopia

Access to improved sanitation safeguards public health, prevents waterborne diseases, and improves overall well-being. However, climate variability can have substantial implications for water availability, hygiene practices, and sanitation infrastructure. The purpose of this paper is to study how precipitation variability influences the choice of sanitation facilities. The paper addresses three research questions: 1) Does precipitation variability cause households to switch from improved to unimproved sanitation systems? 2) Do households switch from private to shared improved facilities (e.g., public toilets) in response to precipitation variability, and 3) Is there heterogeneity in the effects based on the gender of the household head and household location? The study utilizes data from ESS conducted in the years 2011/12, 2013/14, and 2015/16, along with historical weather data from CRU-UEA. The analysis follows a panel fixed-effects approach.

The findings of this study show that increased precipitation variability has a significant impact on sanitation facility choices. Specifically, it

reduces the likelihood of using shared improved sanitation facilities while increasing the use of unimproved sanitation technologies. Higher precipitation variability generally reduces the use of improved sanitation facilities, including both private and shared facilities, without further distinction between them. Notably, the mentioned effects are found to be significant only in households headed by males. The study also provides suggestive evidence indicating that the effect of precipitation variability on sanitation technology choices operates by reducing the utilization of piped water points during the rainy season and decreasing households' annual investment expenditure in water infrastructure.

3.2 Paper II: The role of forest status in households' fuel choice in Uganda

Biobased dirty fuels such as firewood, animal dung, crop residues, and charcoal have adverse health and environmental consequences. Nonetheless, dirty fuels still have a key role in providing lighting, heating, and cooking services in Uganda. This study aims to investigate the relationship between forest conditions and household fuel choice in Uganda. The paper uses EVI as an indicator for forest status and, consequently, firewood scarcity. It hypothesizes that households in areas with more forest vegetation use more biobased dirty fuels, particularly firewood and charcoal. Data from the UNPS collected in 2009/10, 2010/11, and 2011/12 are used in the analysis.

Using the REMNLM-GSEM, the findings show that households in vegetated areas are less likely to rely on dirty biobased fuels and more likely to use mixed fuels than households in non-vegetated areas. Furthermore, we have observed that a greater forest stock is more strongly

associated with a reduced probability of firewood usage, when compared to the use of charcoal. The unexpected role of forest status in the decision to use firewood as a source of energy suggests that the tendency to use firewood is not exclusively influenced by forest stock. There is evidence in the literature that local governments and forest owners use legal or property rights issues to impede others' access to forest resources. Therefore, active forest protection could lessen the use of fuelwood despite an expanding forest stock (Obua *et al.*, 1998; Heltberg *et al.*, 2000). In addition, there is a lack of empirical evidence on the causes of forest degradation in Africa (Rohde *et al.*, 2006; Reenberg, 2012). In this situation, forest policy makers might adopt overly strict forest regulations, endangering local livelihoods.

3.3 Paper III: The impacts of water scarcity on health outcomes: an instrumental variables approach

Climate change challenges freshwater availability, leading to water scarcity, which could affect public health. The study aims to provide evidence on the effects of water scarcity (measured based on water collection time per day per household) on diarrhea prevalence and health insurance purchase in the context of Ethiopia. The analysis incorporates data from the ESS conducted in 2013/14 and 2015/16, historical weather data extracted from CRU-UEA, and the WQT data. It exploits exogenous variations in temperature shocks that households have experienced over the past 30 years prior to the survey periods (2013/14 and 2015/16) as an instrument for water scarcity.

There are several conclusions from this paper. First, we show that water scarcity both raises the prevalence of diarrhea and purchases of health insurance. Second, water scarcity has an effect on the prevalence of

diarrhea among both adults and children under the age of seven. Third, females under the age of seven exhibit a higher vulnerability to diarrhea caused by water scarcity compared to males in the same age group. There are two possible explanations for how water scarcity affects health outcomes. First, increased water scarcity has an impact on sanitation, which encourages households to use more open defecation rather than improved pit latrines. Second, water scarcity makes it more likely that people will fetch water from unimproved sources. The analysis validates the instrument using the WQT data and concludes that temperature shocks do not exacerbate the risk of *Escherichia coli* contamination, water electroconductivity, hardness, and fluoride content. These findings alleviate concerns about temperature shocks impacting water quality and subsequent health outcomes, beyond the water scarcity channel. The impact of water scarcity on health insurance purchases is analyzed using cross-sectional data, and therefore, may not provide strong causal evidence.

3.4 Paper IV: The effects of temperature on farm labor market outcomes in Ethiopia

Family labor, hired labor, and free labor from social networks are the main sources of labor for rural households. The purpose of this paper is to examine how temperature impacts the allocation of farm labor sources and the corresponding wage expenditures throughout the planting, harvesting, and whole agricultural seasons in Ethiopia. The study utilizes ESS data from 2011/12, 2013/14, and 2015/16 in conjunction with high-resolution monthly temperature and precipitation data from CRU-UEA. The identification strategy exploits the exogenous variations in seasonal temperature to households after accounting for the village and district-by-

year fixed effects. Following Correia *et al.* (2020) and Heyes and Saberian (2022), the analysis employs the PPML-HDFEM.

The findings show that higher temperature reduces the demand for hired farm labor during the planting and harvesting seasons. The study highlights the heterogeneity of effects based on parents' sector of employment (agriculture, manufacturing, construction, and services), as well as the administrative regions where households are located. This paper also discusses the mechanisms, showing that temperature negatively affects both labor productivity (kg/labor hours for family labor, and kg/labor days for hired labor and free labor) and land productivity (kg/ha) in agriculture. Increased temperatures also lead to a decrease in the application of fertilizer on agricultural land. However, there is no statistically significant effect of temperature on the use of defensive, loss-reducing, adaptive farm inputs such as pesticides. This suggests that there is no indication of farm input substitution to account for the adverse impact of increasing temperatures on the demand for hired labor.

4. Contribution and policy implications

The contribution of the doctoral thesis to knowledge and policy are presented in this section. The contributions are first covered, followed by policy implications and suggestions for future research.

4.1 Contribution

The thesis contributes empirically and methodologically to the economic analysis of the impact of climate change and resource scarcity on household decisions. Empirically, the four papers combine large-scale, nationally representative household panel data with high-resolution, location-matched weather data to address the shortcomings of earlier studies confined to small samples in geographically constrained areas. In this regard, the thesis provides micro-level empirical evidence on how climate change and resource scarcity affect sanitation and health outcomes, and fuel choice. The thesis also explores the use of unimproved sanitation systems, health insurance, and labor time allocation as strategies for household adaptation to weather and climate change.

The majority of previous studies on resource scarcity rely on self-reported indicators of natural resource scarcity, such as the amount of time spent collecting firewood and water. However, these methods might result in measurement errors due to recalling and reporting problems. The thesis

employs two approaches to tackle these methodological concerns. In paper II, the thesis uses a method from the forest sciences called EVI to reflect the availability of forests and biomass richness. EVI is a preferred proxy compared to time spent fetching firewood or distance to firewood source due to its objective assessment of vegetation abundance, including forests. It provides a comprehensive perspective on forest availability by considering overall vegetation health and density. This is an improvement in comparison to previous approaches that have been based on measuring firewood collection time (Heltberg *et al.*, 2000; Palmer and MacGregor, 2009; Guta, 2012; Guta, 2014; Lee *et al.*, 2015) or measuring the distance to the source of firewood in meters (Heltberg, 2005).

The utilization of the IV/2SLS approach in the third paper, combined with falsification tests, differentiates the effect of water scarcity on diarrhea specifically, rather than non-water-borne diseases. This approach also verifies that the reporting of diseases is not affected by households' strategic behaviors, which further reduces concern for measurement errors in the dependent variables. By implementing a range of tests that help mitigate potential biases in the estimates, we address an aspect that previous research on the subject, such as Usman *et al.* (2019) do not examine.

4.2 Policy implications

The findings of the first paper have implications for sanitation infrastructure planning and development. The results suggest that policymakers should consider location-specific exposure to flooding and maintenance of water and sanitation facilities. Targeted interventions can be designed to promote access to safe and sustainable sanitation options in areas prone to certain precipitation patterns. It is important to develop

reliable drainage systems and flood-resistant sanitation facilities. The second paper provides support for policy interventions that promote agroforestry practices, combining tree planting with livestock rearing and crop cultivation. It suggests that households using a combination of clean and dirty fuels in more forested areas are moving in the right direction towards using clean fuels. Policymakers can support these households by enhancing accessibility to electricity grids and expanding the capacity for production and distribution of LPG. These measures could promote access to environmentally friendly sustainable energy sources.

The results from the third paper can inform policymakers to collaborate with insurance providers to develop innovative insurance products tailored to address specific health challenges arising from water scarcity. Interventions focused on developing water infrastructure to ensure clean water supplies can also be beneficial. The findings from the last paper could be useful in the development of flexible labor policies that consider the effect of temperature changes on labor demand. This could include seasonal employment policies and social safety nets for farm workers who are more susceptible to changes in labor demand brought on by temperature.

4.3 Future research suggestions

The thesis has limitations. This section emphasizes potential areas for future research that address these limitations. In addition to affecting the use of sanitation facilities, increased precipitation variability can play a role in spreading waterborne diseases and vector-borne diseases. Precipitation variability could also have the potential to influence the occurrence of crop failures and livestock diseases. With better data, future research can therefore address the effects of precipitation variability on the spread of

diseases like cholera and malaria as well as nutritional outcomes. The second paper lacks an investigation into the role of forest property rights, institutional factors, and energy use intensity on households' fuel choice due to data limitations. As a result, this thesis recommends future data collection efforts and research to consider exploring these relationships. This has the potential to advance our understanding of the complex dynamics involved and enable to develop more informed policies to promote sustainable energy practices.

The analysis in paper III that examines the relationship between water scarcity and the purchase of health insurance may have limitations due to the use of cross-sectional data. Establishing a strong causal inference in this framework may be challenging. Nonetheless, this analysis can serve as an initial stepping stone for future research endeavors that aim to explore this area more extensively. The fourth paper provides insights that can serve as a foundation for a comprehensive study on the importance of social capital and informal labor networks as key sources of farm labor in the face of temperature fluctuations. This particular study focuses on short-run weather variations. As a result, the estimates are interpreted in terms of short-term weather effects rather than climate, as suggested by Auffhammer (2018) and Kolstad and Moore (2020). Future studies can close this gap.

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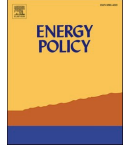
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The role of forest status in households' fuel choice in Uganda

Bahre Gebru^{a,b,*}, Katarina Elofsson^{a,c,d}

^a Swedish University of Agricultural Sciences, Department of Economics, Sweden

^b Mekelle University, Department of Economics, Ethiopia

^c Aarhus University, Department of Environmental Science, Denmark

^d Södertörn University, Department of Social Sciences, Sweden

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ABSTRACT

In this study, we investigate how households' choice of energy source is influenced by the status of the local forest resource. We assume that households choose between clean fuels (e.g., kerosene, LPG, solar, and electricity), dirty biobased fuels (e.g., firewood, animal dung, crop residues, and charcoal), and mixed fuels. We integrate socioeconomic data with high-resolution satellite data on forest conditions from the Uganda National Panel Survey. The findings from a random-effects multinomial logit model indicate that households in vegetated areas are 6–7% less likely to rely solely on dirty biobased fuels, and 6–8% more likely to use mixed fuels, compared to those in non-vegetated areas. A larger forest stock is more strongly associated with lower use of firewood than charcoal. A possible explanation for the findings is the presence of policies for forest conservation and enhanced forest property rights, which improve forest conditions and limit opportunities to collect firewood. Given households' dependence on forest-based fuels, such policies could need to be modified to secure households' access to these fuels.

1. Introduction

In developing countries, dirty biobased¹ energy practices (e.g., firewood, animal dung, crop residues, and charcoal) have both negative and positive effects. On one hand, the use of biobased fuels is dangerous to human health and excessive use of forest fuel can undermine the sustainability of forest ecosystems (Chen and Kuo, 2001; Herington et al., 2016; Shankar et al., 2020). The health impacts comprise respiratory infections for children (Edwards and Langpap, 2012; Heltberg, 2005; Jagger and Shively, 2014), a considerable physical burden associated with firewood collection (Foell et al., 2011), and exposure to air pollution among women involved in cooking (Muller and Yan, 2018). Excessive forest fuel extraction has the potential to degrade forests (Manning and Taylor, 2014) and may over time worsen fuel scarcity (Amacher et al., 1993; Baland et al., 2017; Burke and Dundas, 2015; Manning and Taylor, 2014). On the other hand, firewood collection facilitates income generation (Ektvedt, 2011; Kamanga et al., 2009; Kim et al., 2017), and the collection and use of biobased fuels is an important

part of culture and daily life (Mazzone et al., 2021).

Compared to dirty biobased fuels, so-called clean energy sources like kerosene, LPG,² solar energy, and electricity, have a wider range of applications,³ are less hazardous to human health, and are easier to use (Stern, 2010). Utilizing such energy sources also lessens the strain on forest health status (Garland et al., 2015; Government of Uganda, 2015). Therefore, it is frequently suggested that initiatives aimed at promoting the transition to clean energy should be encouraged (Lee, 2013; Smith, 2002). Different policy instruments, such as information campaigns advocating improved and more efficient biomass stoves, or subsidy schemes to cover the expenses of the poor for adopting new technology in order to stimulate a fuel switching process, could be used (Heltberg, 2005). Such a transition is argued to be particularly important where fuelwood is an important fuel (Edmonds, 2002; Fisher, 2004; Heltberg et al., 2000) and forest degradation is a serious problem. For any policy program intending to achieve conversion towards clean fuels, or enhanced forest status, it is important to understand how households respond to changes in forest condition (Bandyopadhyay et al., 2011).

* Corresponding author. Swedish University of Agricultural Sciences, Department of Economics, Sweden.

E-mail address: bahre.kiros@slu.se (B. Gebru).

¹ Dirty fuels are also called traditional or inferior fuels in the literature.

² Liquefied Petroleum Gas.

³ For instance, solar energy can be utilized for a variety of tasks, including lighting, cooking, and charging mobile devices. Batteries in mobile phones, however, cannot be charged with firewood.

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Knowledge about these responses is valuable because it improves the understanding of the magnitude of policy interventions required, and how policies could affect forest conditions in different localities.

Evidence on the links between forest degradation, firewood collection, and fuel choice is scant (Heltberg et al., 2000; Pattanayak et al., 2004). Relatively few studies examine the effect of firewood scarcity on fuel choice. These studies measure firewood scarcity in different ways. Some studies make use of economically related scarcity indicators, such as the price of firewood (Alem et al., 2016), the total firewood collection time (Guta, 2012, 2014; Lee et al., 2015; Palmer and MacGregor, 2009), and the average firewood collection time (Heltberg et al., 2000), where the latter two are used as indicators of opportunity costs of firewood. These measures have limitations. For example, the market price of firewood does not fully reflect firewood scarcity because the energy input market is not well-functioning in Africa (Cooke et al., 2008). Heltberg (2005) uses a physical measure, the distance to forests, that indicates households' potential access to collectable firewood. Heltberg et al. (2000) consider both average fetching time, forest access, and forest stock. They measure forest stock as the ratio of the village population number to forest area. A lower ratio then indicates a greater incentive to substitute non-forest fuels, such as animal dung and crop residues, for forest firewood. The other forest related variable, forest access, is measured by the village population number relative to the total area of the village, where higher ratio is expected to induce a larger use of non-forest fuels.

Common to the mentioned studies is that the proxies for firewood scarcity are almost always obtained from self-reported data. Such self-reported data have drawbacks (Burivalova et al., 2015) because they could include measurement errors. When household heads report, for example, the time spent gathering firewood or the distance travelled by each household member, recording and recalling issues may arise. In contrast, Jagger and Kittner (2017) use a different approach, examining the connection between household energy preferences and biomass availability as measured by a satellite-based measurement of land cover change. However, their study is limited to agriculture-driven deforestation in west central Uganda and contains few observations (902 households).

The purpose of this study is to examine the role of forest status in households' fuel choice. We assume that households choose between clean and dirty fuels, or a mix thereof, and hypothesize that households in areas with more forest vegetation use more biobased dirty fuels, in particular firewood and charcoal. To avoid the above mentioned problems associated with self-reported data on firewood scarcity, we use the Enhanced Vegetation Index (EVI)⁴ as an indicator of forest status. The EVI is a satellite based measurement of surface vegetation greenness used to reflect variations in forest availability and biomass richness of a forest (Ishtiaque et al., 2016). It is a global-based and widely used index for monitoring vegetation activity (Boles et al., 2004; Soudani et al., 2006; Xiao et al., 2004). Admittedly, measurement errors could still be a potential pitfall associated with remote sensing data (Donaldson and Storeygard, 2016). For example, classification of forest status into non-vegetated, sparsely vegetated, and densely vegetated areas based on such data (Hasanah and Indrawan, 2020) could involve a subjective component. We address this problem by using a continuous measure of the forest status variable as a robustness check.

The analysis is applied to Uganda. This choice is motivated by the country's strong dependence on firewood, in combination with political ambitions to rapidly transit towards cleaner energy. Moreover, disaggregated data on energy utilization is available, and extrapolation of the results to other Sub-Saharan Africa (SSA) countries is relevant because uptake of clean energy and reliability of electricity supply, in particular, is a serious problem in the region at large (Blimpo and

Cosgrove-Davies, 2019). The household socioeconomic characteristics and satellite data on forest status are obtained from a three-round panel dataset from the Uganda National Panel Survey (UNPS) collected during 2009/10, 2010/11, and 2011/12 and made available by the Uganda Bureau of Statistics (Uganda Bureau of Statistics, 2009/10, 2010/11, 2011/12). We model households' fuel choice using the random-effects multinomial logit model (REMNLML) under Generalized Structural Equation Modeling (GSEM) that addresses selectivity bias (Baum et al., 2017).

Our paper makes at least two contributions to the literature. First, it employs a spatio-temporally robust measure of firewood scarcity at household level, thereby improving on earlier studies. Also, the use of remote sensing data, which can be linked to field-based household data, allows us to obtain data with high spatial resolution. Second, unlike most previous research on similar topics that typically relies on cross-sectional data (Alem et al., 2016), we use panel data that takes into account socioeconomic, housing, environmental, and weather variables that are not commonly controlled for in earlier studies.

The remainder of the paper is organized as follows. Section 2 provides the context of the study. Section 3 describes the data, and section 4 presents the econometric methods. Section 5 discusses the results, and section 6 concludes.

2. Case study background

This section briefly presents the background regarding the socio-economic situation, forest status, fuel use, and energy policy targets in Uganda.

2.1. Socioeconomic context

Uganda has a population of about 42 million. Above 15% of the population is between the ages of 0 and 14. Over the period 2009/10 to 2011/12, the percentage of female-headed households is 44%, see Table A.1 in the Appendix. In Uganda, migration is common. Young individuals between 15 and 34 years make up 55% of the movers. Migration could affect landscapes in protected areas. For example, Harter et al. (2015) document that areas surrounding Kibale National Park in western Uganda have changed from being sparsely settled bushland to a heavily settled subsistence farming landscape due to migration.

The UNPS shows that close to 70% of the working age (14–64 years) group are self-employed in the country. More women than men are unemployed. The majority of men work in paid jobs, whereas the majority of women are self-employed. Most people work within the agriculture and service sectors. Poverty is a persistent problem, and about 10% of the population remained chronically poor during the studied time period (Uganda Bureau of Statistics, 2011/12).⁵

Farming households typically receive land as an inheritance or gift. Of the agricultural households, 34% are involved in crop production, 11% are engaged in livestock rearing, and 10% practice mixed farming. Other households are involved in, e.g., mining and quarrying, manufacturing, and construction. The main crops are bananas, sweet potatoes, and beans and maize. The percentage of farmers raising cattle, goats, sheep, and pigs decreased over the study period, while the percentage of households engaged in poultry farming increased. The latter can be linked to a growing market for local birds and new breeds of chicken. Likewise, the percentage of households rearing small animals increased (Uganda Bureau of Statistics, 2011/12).

Uganda is a diverse country in terms of ethnicity (or tribes), culture and religion. The dominant tribes are Baganda (18.61%), Banyakole

⁴ The EVI data is measured based on household locations by enumeration areas in Uganda.

⁵ These households are female-headed, polygamous married, and/or led by household heads having no formal education. Geographically speaking, they are mostly located in the country's North.

(9.21%), Langi (8.43%), Basoga (7.18%), Bakiga (6.95%), and Iteso (6.92%). There are 42 indigenous languages, with English and Swahili being official languages (Hamilton et al., 2016), and Christianity and Islam account for about 82% and 14% of the population, respectively (International Religious Freedom Report, 2019).

2.2. Forest status

Uganda's forests include alpine, tropical high- and medium-altitude forests, woodlands, wetland and riparian forests, plantations and trees (Obua et al., 2010). Private and customary land comprise about 70% of the forest, while local governments administer some public forests. Forest reserves are available on public land, and are protected by law. The woodlands are mostly privately owned. Natural forests and shrubs dominate Uganda's vegetation (Bamwesigye et al., 2020). Forest structure and composition varies across the country due to differences in altitude, soil type, drainage, and human activities (Hamilton, 1984). Langdale-Brown et al. (1964) grouped the Ugandan forests into medium altitude-moist-evergreen forest, medium altitude-moist-semi-deciduous forest, and high-altitude forest. The first type of forest is structurally complex and rich in species, including *Peptadeniastrum-Uapaca* (in Sese islands), *Peptadeniastrum-Albizia-Celtis* (in drier lake shores), and *Parinari excelsa* (in western rift valley). Representative plant species for the medium altitude-moist-semi-deciduous forests are *Celtis-Chrysophyllum* (north of Lake Victoria), *Cynometra-Celtis* (along the western rift), *Albizia-Milicia excelsa* (to the north of Lake Victoria), and *Albizia-Markhamia* (mid-west). The high-altitude forests have fewer species, e.g. *Prunus* moist sub-type, and typically a broken and irregular canopy. These forests are found in south-west Uganda.

Forest degradation is a problem. High population growth leading to increased demand for forest products, and weak governance of settlements and forests contribute to this (Obua et al., 2010). Private and publicly owned forests are both important sources of firewood and charcoal (Khundi et al., 2011), and therefore affected by this demand. In an effort to enhance forest management, Uganda is undergoing a transition to a more decentralized system, where about 70% of the forests are managed by the country's District Forestry Service,⁶ while the remaining area falls equally under the National Forestry Authority⁷ and the National Wildlife Authority.⁸

2.3. Fuel use

In Uganda, biomass accounts for over 90% of the energy supply (Okello et al., 2013; Turyareeba, 2001), and firewood serves as a primary source of energy in about 89% of the households (Government of Uganda, 2015). Animal dung and crop residues account for 4.8% of the country's primary energy consumption (Okello et al., 2013). Low forest biomass availability in west central Uganda forces households to instead rely on crop residues for cooking, or to collect non-forest based firewood which has a lower quality than forest-based firewood. Based on observed collection time, firewood scarcity in Uganda seems to be increasing over time (Jagger and Kittner, 2017).

Clean energy sources account for less than 10% of total energy consumption: of this, petroleum fuels (e.g., gasoline, diesel fuel, kerosene, fuel oil, aviation fuel, and LPG) make up 7.4%, and electricity 1.1%. Thus, Uganda is one of the countries with the lowest access to electricity in Africa (Okello et al., 2013). It is argued that the national electricity supply has serious reliability problems, which is a challenge

to the adoption of new technologies (Blimpo and Cosgrove-Davies, 2019).

2.4. Energy policy targets

The Ugandan government has set a target to reduce national wood consumption by 40% by 2030. In accordance with the UN Sustainable Energy for All initiative, it also aspires to promote access to clean energy services, including access to electricity and modern cooking solutions for all in the same target year (Ministry of Energy and Mineral Development, 2017). In order to achieve these targets, millions of households must acquire LPG stoves, or improved wood and charcoal stoves. Achieving this will be a challenge given the country's annual production capacity of 300,000 clean stoves, their short lifespan, inadequate stove distribution centers, and LPG companies being concentrated in the capital city Kampala (Government of Uganda, 2015).

3. Data and measurements of forest status

The UNPS includes seven survey rounds that span from 2009/10 to 2019/20. The present study makes use of data from three survey rounds: 2009/10, 2010/11, and 2011/12 (Uganda Bureau of Statistics, 2009/10, 2010/11, 2011/12). The inclusion of more recent survey rounds is not possible because data on our chosen indicator for forest status is not publicly available for more recent survey rounds.

The UNPS is suitable for fuel choice analysis in the African context because the survey contains a detailed energy use section. From this section, we use the question "Do you use [list of fuels] for cooking, lighting, and heating?". We elicit whether or not a particular household is using clean energy sources (e.g., kerosene, LPG, solar, and electricity), dirty biobased energy sources (e.g., firewood, animal dung, crop residues, and charcoal), or a mix of those. The UNPS questionnaire asks if households use a specific fuel and the amount consumed in different, relevant units (e.g., kg, liter, or bundle, where the latter applies to firewood). However, the fuel quantities and measurement units are largely missing in the data, and it is not clear how the measurements should be converted into a single uniform unit. Therefore, we do not use such quantitative data in our econometric analysis.

The classification of fuels as being clean or dirty used in this study is based on their effects on health and natural resource conditions (Pachauri and Jiang, 2008). Kerosene, however, is classified as clean in some studies (Alem et al., 2016; Foell et al., 2011; Viswanathan and Kavi Kumar, 2005), and dirty in others (Rahut et al., 2014). In this paper, we place it in the clean category, motivated by the low local environmental impact (Kavi Kumar and Viswanathan, 2007), despite its global impact on climate change.

Throughout the paper, a household is defined as using clean energy if it uses at least one clean energy input but not any dirty fuel. Correspondingly, households defined as using dirty energy use at least one dirty fuel, but not any clean source. Households are categorized as using mixed energy if they use at least one clean and at least one dirty source. Biobased fuels from forests and agricultural land are all included in the dirty energy category. However, as our main purpose is to investigate the effect of forest status on fuel choice, it is also necessary to specifically focus on forest fuels. We therefore also carry out analysis where forest fuels are treated separately from the other dirty fuels, and separately from each other, which is further explained in Section 4 below. The UNPS includes areas from the 2005/06 Uganda National Household Survey (UNHS).⁹ There were 34 enumeration areas (EAs) in Kampala District and 72 others¹⁰ in the Central, Eastern, Western, and Northern regions. All UNPS rounds attempt to keep the same households across

⁶ A local government unit responsible to manage land and forest resources outside of national parks.

⁷ The National Forestry Authority administers central and local forest reserves.

⁸ National Wildlife Authority advises on matters pertinent to land use in and off national parks, enforcement of use rights within parks being the major task.

⁹ Before UNPS, UNHS surveyed households to measure national poverty in Uganda. Since 1999, it has collected data on 17,450 households in 112 districts. ¹⁰ 58 rural and 14 urban EAs.

survey rounds. The inclusion of Kampala, other urban, and rural areas of all regions ensure representation in the UNPS strata. UNPS randomly selects EAs and households from each EA.

To identify the role of forest status in households' decisions on energy use, we need an indicator of forest viability. Forest biomass is such an indicator. The concept 'biomass' broadly includes both above-ground and below-ground living mass, but most studies focus on above-ground biomass due to the difficulty in collecting data on below-ground biomass (Lu, 2006). Remotely sensed data uses vegetation indices (VIs) to measure forest biomass. The VIs are calculated based on vegetation properties and variations of structural canopy (Huete et al., 2002b; Shen et al., 2010), and can be used for vegetation classification (Huete et al., 1999). The most commonly used VIs are the EVI and the Normalized Difference Vegetation Index, NDVI. The present paper is based on the EVI. The EVI is introduced as an improvement over NDVI by optimizing the vegetation signal where NDVI saturates (Huete et al., 2002a). The EVI removes both atmospheric and background noises simultaneously (Wang et al., 2003), and has proved to perform better than NDVI in many empirical applications (Huete et al., 1999; Liu and Huete, 1995). The value of the EVI falls between 0 (bare ground) and 1 (healthy vegetation). A detailed technical presentation of EVI is provided by Liu and Huete (1995), Huete et al. (1994) and Huete et al. (1997). Forest scientists also use NDVI to differentiate vegetated regions from non-vegetated ones, with an index falling between -1 and +1 (Tucker, 1979). The higher the NDVI value, the greater the density of the forest. While lower values indicate sparse vegetation, negative values commensurate to waterbodies. However, the NDVI estimation is less effective for our purpose since it is very sensitive to fluctuating atmospheric and canopy background conditions (Gao, 1996; Liu and Huete, 1995).

Finally, there is a connection between the socioeconomic data (such as household roster, education, housing conditions, and energy use) and the satellite data on forests from UNPS. These datasets have unique household ID numbers in common. This unique identifier matches the datasets together and makes them ready for analysis. The household-level analysis has an unbalanced panel with 6270 observations in the full sample. The regions, sample households, and forest conditions in Uganda are shown in Fig. 1.

4. Econometric methods

On an aggregate level, the use of forest fuels can lead to a decline in forest status. This should be taken into account by a social planner when deciding on the optimal level of fuelwood extraction. However, for an individual household the same feedback effect from their private fuelwood collection decision is likely to be small or negligible when there are many neighbouring households also collecting fuelwood. In our analysis, we therefore assume that the forest status is exogenous to individual households. In our regressions, the dependent variable is whether the fuel sources of household i at time t are clean ($j = 1$), dirty ($j = 2$) or mixed ($j = 3$). The utility of the i^{th} household from any fuel source category is modeled as:

$$Choice_{it} = \theta_j Forest_{it} + X'_{it} \beta_j + \epsilon_{ijt} \tag{1}$$

where $Choice_{it}$ is the category of the chosen fuel by household i at time t into $j = 1, 2, 3$. The variable $Forest_{it}$ is an EVI-based indicator of forest status in the neighbourhood of household i at time t , and θ_j is the coefficient of interest. Following Hasanah and Indrawan (2020), we chose to classify EVI into 3 groups, reflecting the extent of forest status: non-vegetated if $0 \leq EVI \leq 0.35$ (yes = 1), sparsely vegetated if $0.36 \leq EVI \leq 0.5$ (yes = 2), and densely vegetated if $0.51 \leq EVI \leq 1.0$ (yes = 3).

The variable X' is a vector of other explanatory variables with β_j as the associated vector of coefficients. These are household variables (e.g., education of the household head, age, gender, and family size), economic variables (e.g., land size, livestock size, and wealth measured in terms of consumption spending), housing variables (e.g., number of rooms, independent, shared residence, and other), environmental variables (plain, plateau, and mountainous areas), and weather variables (e.g., mean rainfall and temperature). The inclusion of these variables is motivated by the literature on household fuel choices, and ensures that we minimize estimation bias in θ_j .

We hypothesize that more educated household heads tend to shift from dirty to clean fuels. Higher income is expected to have a similar effect, in accordance with the energy ladder hypothesis (Guta, 2012; Heltberg, 2005). Households with higher expenditures are hypothesized to use more clean or mixed fuels, but less of dirty energy

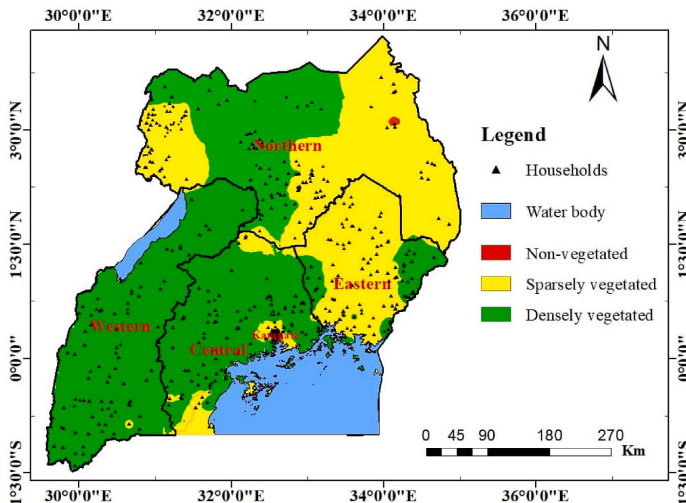


Fig. 1. UNPS regions, sample households, and forest status in Uganda.

(Gebreegzabher et al., 2012; Guta, 2012). The literature reports that larger families use more firewood (Cruz et al., 2020; Ouedraogo, 2006), and less clean fuels and charcoal (Ouedraogo, 2006). Female-headed households will rely more on dirty biobased fuels (Guta, 2012; Ouedraogo, 2006). In addition, households with larger land and livestock holdings could use more dirty biobased fuels (Guta, 2012). Housing factors may affect fuel choice. Heltberg (2005) reports that the number of rooms is positively related to the use of LPG. As observed in Burkina Faso the type of dwelling matters, for example, tenants that share a yard have more limited space for firewood storage facilities (Ouedraogo, 2006). We use environmental landscape factors as control variables in the econometric specifications because they affect the level of infrastructural investments (Yamada and Yamada, 2021), and thus installation of electricity. Weather conditions can also affect energy choice (Auffhammer and Mansur, 2014; Ektvedt, 2011; Mazzone et al., 2021). For example, most firewood in Peru is collected during dry seasons, when agricultural activity is less intense (Ektvedt, 2011). Finally, the variable ϵ_{ijt} is the random error term, assumed to be independently and identically distributed, and follows type I extreme value distribution.

In spite of the inclusion of control variables, some situations could still result in wrong θ_j estimates in Eq. (1). First, there could be a potential endogeneity problem due to omitted variables bias. We follow the literature and address the problem through the inclusion of a latent variable, \mathcal{L}_{it} , in our model (Baum et al., 2017; Nkegbe et al., 2018). \mathcal{L}_{it} is included in each energy equation, and its variance is constrained to one to allow estimation of its magnitude in the equations. Second, the coefficient θ_j could be biased if there are regional characteristics that affect the outcome variables differently across regions. For example, Himbara (1994) shows that investors channel their investment projects towards areas where their ethnic groups are located. There can also be cultural and behavioral differences in fuel use across locations (Cruz et al., 2020; Farsi et al., 2007; Heltberg, 2005; Kim et al., 2017), differences in population density, infrastructural development, resource availability and accessibility, and plants species suitable for firewood use (Jiménez-Escobar et al., 2021) that affect fuel choice. We address these concerns by controlling for region fixed-effects (u_R). The year fixed-effects (u_t) address variations in fuel choice across survey rounds.

Third, Eq. (1) overlooks the unobserved heterogeneity between units entailing within-unit dependence and ignores the independence of irrelevant alternatives (Alem et al., 2016; Skrondal and Rabe-Hesketh, 2014). With the exception of Alem et al. (2016), previous studies that make use of a panel multinomial logit model, such as Guta (2012), do not take these concerns into account. The estimates based on such studies are therefore inconsistent and inefficient (Malchow-Møller and Svarer, 2003). In our study, we use REMNLM (Chen and Kuo, 2001; Malchow-Møller and Svarer, 2003; Rabe-Hesketh et al., 2004) in the GSEM setup to specifically address these issues. This approach allows for a correlation among the residuals for the clean, dirty, and mixed energy equations within the same household, and assumes independent residuals across households. The REMNLM considers survey round (t) at level 1 and household (i) at level 2 to account for the time-invariant unobserved household heterogeneity, a_{ij} .

Addressing the aforementioned problems, Eq. (2) presents the REMNLM equation:

$$Choice_{ijt} = \theta_j Forest_{it} + X'_{it}\beta_j + \mathcal{L}_{it} + u_t + u_R + \alpha_{ij} + \epsilon_{ijt} \quad (2)$$

The multinomial model is given by:

$$P(j|Forest_{it}, X_{it}, \alpha_i) = \frac{\exp(\theta_j Forest_{it} + X_{it}\beta_j + \alpha_{ij})}{\sum_{z=1}^J \exp(\theta_z Forest_{it} + X_{it}\beta_z + \alpha_{iz})} \quad (3)$$

After calculation of the sample likelihood for the random-effects model by integrating over the distribution of the unobserved heterogeneity, the Full-Information Maximum Likelihood Estimator (FIMLE) is used.

The precise effect of forest status could differ across different types of dirty fuels. We expect larger availability of forest biomass to be positively associated with the use of wood fuels such as firewood and charcoal. Moreover, charcoal can be potentially transported between regions. The market is well integrated (Branch and Martiniello, 2018) and charcoal is highly traded compared to firewood. We therefore expect the effect of local forest status on firewood to be higher than that on charcoal. We address these differences among dirty biobased fuels by using three alternative definitions of dirty energy, summarized in Table 1. The baseline model, which is reported in panel A of Table 3, and Tables A.3 and A.4 in the Appendix, includes all biobased fuels in the dirty category, below referred to as Dirty-I. In the second case, households are defined as using dirty fuels if they use firewood and, potentially, also other dirty fuels. In the third case, households are defined as using dirty fuels if they use charcoal and, potentially, also other dirty fuels. The last two alternative dirty fuel categories are labeled as Dirty-II and Dirty-III in Table 1. Using these alternative definitions, we are able to specifically identify the role of forest status in firewood and charcoal use. Combinations of clean and dirty fuels are referred to as mixed fuels, and the definition of Mixed-I to III follows from that of Dirty-I to III. Thus, Mixed-I implies that a combination of clean fuels, and fuels included in Dirty-I, are used. The definitions of Mixed-II and III follow the same logic. The non-wood dirty fuels (i.e., crop residues and animal dung) are not directly dependent on forest conditions. However, it could also be relevant to study the specific impact on these fuels because forest policy could lead to switch away from using forest fuels (Heltberg et al., 2000). These estimations are presented in panel C of Table A7.

Some variables in the X_{it} vector need to be transformed into logarithms to ensure a normal distribution. However, the log is sometimes undefined for the variables land size, number of rooms, tropical livestock unit (TLU), and household head's year of education, which contain cases with zero values. We solve this problem and retain the zero-value observations by applying the inverse hyperbolic sine transformation approach (IHSTA). For any random variable x , the IHSTA becomes $\ln(x + \sqrt{x^2 + 1})$ (Bellemare and Wichman, 2020; Burbidge et al., 1988; Ravallion, 2017).

Table 1
Different definitions of dirty and mixed energy sources used in Table 3, and A.3 and A.4.

Panels	Cases	Any clean used	Any dirty used	Firewood (+other dirty) used	Charcoal (+other dirty) used
Panel A	Clean	X			
	Dirty-I		X		
	Mixed-I	X	X		
Panel B	Clean	X			
	Dirty-II			X	
	Mixed-II	X		X	
Panel C	Clean	X			
	Dirty-III				X
	Mixed-III	X			X

Note: The energy utilization 'cases' are defined as follows. Clean shows the household completely depends on at least one of the clean energy sources in all panels (Any clean used). Dirty-I implies the dirty fuels consisting of both wood fuels (firewood and charcoal) and non-wood fuels (crop residue and animal dung), labeled as 'Any dirty used'. Dirty-II means the household uses firewood or combines it with other dirty fuels (Firewood (+other dirty) used). Finally, Dirty-III indicates the household uses charcoal alone or in combination with other dirty sources (Charcoal (+other dirty used)). The definitions of Mixed-I, Mixed-II, and Mixed-III directly follows the definitions of Dirty-I, Dirty-II, and Dirty-III together with clean in each panel, respectively.

Table 2
Summary statistics.

Variable	Panel A: EVI (%)							
	Year 2009/10		Year 2010/11		Year 2011/12		Pooled	
	Mean	N	Mean	N	Mean	N	Mean	N
EVI	0.484	1955	0.515	2077	0.509	2238	0.503	6270
Variables	Panel B: Households location based on forest status (%)							
	Year 2009/10		Year 2010/11		Year 2011/12		Pooled	
	Mean	N	Mean	N	Mean	N	Mean	N
Forest status								
Non-vegetated	11.71	1955	6.40	2077	6.03	2238	7.93	6270
Sparsely vegetated	44.65	1955	26.53	2077	36.77	2238	35.84	6270
Densely vegetated	43.63	1955	67.07	2077	57.19	2238	56.23	6270
Fuel usage	Panel C: Households consuming different fuel inputs (%)							
	Year 2009/10		Year 2010/11		Year 2011/12		Pooled	
	Mean	N	Mean	N	Mean	N	Mean	N
Dirty energy								
Firewood	.789	1955	.809	2077	.83	2238	.81	6270
Animal dung	0	1955	0	2077	.004	2238	.001	6270
Crop residue	.09	1955	.089	2077	.09	2238	.089	6270
Charcoal	.298	1955	.266	2077	.252	2238	.271	6270
Clean energy								
Kerosene	.884	1955	.842	2077	.805	2238	.842	6270
LPG	.006	1955	.003	2077	.005	2238	.005	6270
Solar	.009	1952	.018	2077	.019	2238	.015	6267
Electricity	.13	1951	.095	2073	.083	2237	.102	6261
Energy categories (%)	Panel D: Percentage of households in different energy categories							
	Year 2009/10		Year 2010/11		Year 2011/12		Pooled	
	Mean	N	Mean	N	Mean	N	Mean	N
Clean energy sources	2.61	1955	2.21	2077	1.70	2238	2.15	6270
Dirty energy sources	6.91	1955	10.35	2077	14.83	2238	10.88	6270
Mixed energy sources	90.49	1955	87.43	2077	83.47	2238	86.97	6270
Fuel channels (%)	Panel E: Percentage of households using different channels for obtaining fuels							
	Year 2009/10		Year 2010/11		Year 2011/12		Pooled	
	Mean	N	Mean	N	Mean	N	Mean	N
Market purchase	25.53	1892	24.64	2029	22.29	2198	24.07	6119
Self-collection	67.65	1892	68.90	2029	71.97	2198	69.62	6119
Purchase and collection	6.82	1892	6.46	2029	5.73	2198	6.31	6119

Table 3
Marginal effects: the role of forest status in fuel choice (non-vegetated being the base category).

Variables	Dependent variable: fuel choice									
	Panel A: Basket of dirty fuels			Panel B: Firewood used			Panel C: Charcoal used			
	Clean (1)	Dirty-I (2)	Mixed-I (3)	Clean (4)	Dirty-II (5)	Mixed-II (6)	Clean (7)	Dirty-III (8)	Mixed-III (9)	
Sparsely vegetated	-0.000 (0.005)	-0.061*** (0.012)	0.061*** (0.014)	-0.015** (0.006)	-0.072*** (0.015)	0.087*** (0.017)	-0.005 (0.017)	-0.040* (0.021)	0.045* (0.025)	
Densely vegetated	-0.006 (0.005)	-0.074*** (0.013)	0.080*** (0.014)	-0.020*** (0.006)	-0.090*** (0.017)	0.110*** (0.018)	-0.023 (0.014)	-0.021 (0.015)	0.044** (0.020)	
Latent variable, L		-2.56e-15** (1.07e-15)	-2.56e-15** (1.07e-15)		-5.40e-15** (1.17e-15)	-5.40e-15** (1.17e-15)		1.21e-11* (7.15e-12)	1.21e-11* (7.15e-12)	
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Region fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	
Heterogeneity indicators										
Variance (L)		1 (constrained)			1 (constrained)			1 (constrained)		
Variance (equations)	1.18e-07*** (7.20e-09)			4.75e-08** (3.18e-09)			14.251*** (4.641)			
Observations	6270	6270	6270	5215	5215	5215	1834	1834	1834	

Note: The dependent variable is whether or not the household chooses (a) at least one of the clean energy sources but not any dirty fuel inputs in columns 1, 4, and 7; (b) at least one of the dirty energy sources excluding any clean energy in column 2; (c) firewood as a dirty energy but not any other clean energy in column 5, and (d) charcoal as a dirty energy distinct from all clean energy sources in column 8 for cooking, lighting, and/or heating purposes. The definitions of mixed energy I to III in columns 3, 6, and 9 varies depending on the definitions of dirty energy I to III in each panel. The answers are coded as 1 if yes and 0 otherwise for each column in panels A to C. Other controls appear in Table A.2 in the Appendix. Columns 1–9 are REMNLM fitted with GSEM. Robust standard errors clustered at the household level are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

5. Results and discussion

This section provides the results. It begins with the descriptive analysis, followed by the empirical results.

5.1. Data description: the EVI, energy utilization and energy sources

This sub-section provides a description of the data on EVI and household energy utilization across years, with summary statistics reported in Table 2. The average EVI is 0.5 for the pooled sample with improvements in forest biomass availability between the survey rounds 2009/10 to 2010/11. The average EVI slightly falls during 2011/12 as opposed to the preceding year. About 56% of the households are located in densely vegetated areas followed by another 36% and 8% being in sparsely and non-vegetated areas, respectively. Households rely on different energy inputs. Close to 84% of the households report using kerosene as a source of energy. Kerosene is commonly used for cooking and lighting in SSA (Karekezi and Kithyoma, 2002). Firewood is used for cooking, heating, and/or lighting purposes by about 79%, 81% and 83% of the households over the three survey rounds. About 27% of the pooled sample households also use charcoal, while the proportion of households using the remaining energy sources is fairly limited, see panel C of Table 2. The huge majority, close to 87%, of the households use mixed fuels. This is followed by about 11% and 2% of the households solely relying on dirty and clean energy sources, respectively (panel D of Table 2).

The number of households self-collecting fuel, mainly in terms of firewood from own land and their villages increases from 68% in 2009/10 to 72% in 2011/12. At the same time, there is a consistent decline over the years in the proportion of households purchasing energy inputs on the market, or combining market purchases and self-collection (panel E of Table 2). The summary statistics of other control variables can be found in Table A.1 in the Appendix. One can note from Table A.1 that the average land size, including both own land and land with user rights, is 4.5 acres for the pooled sample. The presence of own land helps households to grow different biomass fuels and firewood-targeting trees (Cooke et al., 2008). Also, larger land and livestock sizes may provide households with crop residues and animal dung.

5.2. Empirical results

The main empirical results and robustness checks are presented below.

5.2.1. The role of forest status in fuel choice

This sub-section reports the econometric analysis on the role of forest status in households' fuel choice decisions. Table 3 provides the main results in terms of marginal effects¹¹ estimated by FIMLE.¹² Robust standard errors clustered at the household level are reported. Results for the baseline definition of dirty fuels (Dirty-I) are shown in panel A of Table 3. Columns 2 and 3 show that households switch from dirty to mixed fuels when the forest stock improves. More specifically,

households in areas with sparse and dense vegetation are 6–7% less likely to use dirty energy compared to households in non-vegetated areas (see column 2, panel A of Table 3). This is associated with a corresponding increase in the probability of selecting mixed energy sources, as shown in column 3, panel A of Table 3.

As mentioned in section 4, we explore the specific role of forest status in wood fuel choice by using firewood (Dirty-II) and charcoal (Dirty-III) as necessary components in the dirty energy basket. The associated results are presented in panels B and C of Table 3 for firewood and charcoal, respectively. We find that households' use of firewood is likely to be 7–9% lower with sparse and dense vegetation relative to the non-vegetated localities (column 5, panel B of Table 3). Moreover, there is a simultaneous 1.5–2% reduction in the likelihood of exclusively using clean sources (column 4, panel B of Table 3). Together, this leads to a corresponding increase by 9–11% in the probability of using mixed fuels (column 6, panel B of Table 3).

We also look at how forest status affects the use of charcoal. According to the findings, households in sparse vegetation areas have a lower likelihood of using charcoal compared to those in non-vegetated areas (column 8, panel C of Table 3). The use of charcoal is not affected by dense vegetation. The fact that charcoal is more mobile than firewood may account for the weak statistical effect on charcoal use. In addition, charcoal traders commonly give bribes to forest officials (Jagger and Shively, 2015), fostering the mobility of this fuel across localities. The descriptive analysis supports this: we find that 1247 households rely on purchased charcoal, while only 440 households in the entire sample buy firewood. Column 9 shows the impacts of changing forest conditions on using mixed energy are comparable to those available in panels A and B of Table 3.

The negative effect of forest status on choosing firewood as a fuel source is contrary to expectations. It indicates that forest status is not an exclusive determinant of firewood use. There are at least two potential explanations. First, legal or property rights issues affect forest management and use. Obua et al. (1998) show that local communities in Budongo forest reserve in Uganda dislike strict forest management rules. Locals are not provided with licenses to access non-timber forest products and are deprived of the advantages of the timber industry. As a result, people distrust the forest department. Heltberg et al. (2000) also report restrictions on animal and motor-powered firewood transportation in the Sariska Tiger Reserve in northwest India, and note that well-equipped forest guards can reduce locals' ability to gather firewood. Active forest protection therefore reduces dependence on fuelwood. Second, policymakers lack knowledge on causes of forest degradation in Africa (Fairhead and Scoones, 2005; Reenberg, 2012; Rohde et al., 2006). There is a risk that tougher forest resource management regulations will be introduced to improve forest status, such as prohibitions on collecting even dry and fallen woods from forest areas, affecting locals' livelihoods (Barrett et al., 2013; Edstedt and Carton, 2018; Lyons and Westoby, 2014; Reddy and Chakravarty, 1999; Rohde et al., 2006).

Households' possibilities for adaptation to enhanced private property rights and forest conservation policies vary depending on the economic, environmental, and cultural context. One mechanism is to substitute the non-wood dirty fuels for the wood fuels when access to forests is limited,¹³ which eases the pressure on natural forests (Heltberg et al., 2000). Households could also opt for new fuelwood species as suggested by the diversification hypothesis (de Albuquerque, 2006). One alternative is exotic species, for which the acceptance could vary depending on the cultural context (Jimenez-Escobar et al., 2021). Food preferences can be flexible and affect the demand for firewood (Mazzone et al., 2021). For example, native species can be preferred for their specific characteristics, e.g., hot flame, less smoke, long-lasting flame and embers, and ease of splitting and lighting (Cruz et al., 2020; Kim

¹¹ It is important to note that the marginal effects in each panel would always sum up to zero whenever the REMNLM is used. This is so because a higher coefficient value of a variable in one of the categories of the dependent variable would imply a reduction in the estimates for the other alternatives.

¹² We use separate but correlated random-effects among different energy categories. The estimated variances of the random-effects are statistically significant and highlight the potential importance of common shocks across the fuel choice and forest status circle. These results reveal that the unobserved household heterogeneity component is statistically significant. The coefficient of \mathcal{L} is significantly different from zero in all panels. This confirms that omitted variables would have affected fuel choice if left unaddressed via \mathcal{L} in Eq. (2). The clean energy is a base category when we estimate the effect of \mathcal{L} .

¹³ Panel C of Table A7 in the Appendix supports this idea.

et al., 2017). Evidence from Kenya demonstrates that households prepare composite meals¹⁴ and have dishes that need less time in response to a lack of firewood (Waswa et al., 2020). There are also different cultural preferences in relation to firewood gathering. The majority of rural Vietnamese households, for example, prefer green branches and whole living trees for firewood purposes compared to dry or dead trees (Kim et al., 2017). Also, households may adapt by collecting firewood from new places, including woodlots, bushes, and gardens, and could receive firewood through welfare programs (Jiménez-Escobar et al., 2021; Kim et al., 2017; Waswa et al., 2020).

Regardless of the variations in the definition of dirty energy depending on the panels, our results consistently show an increase in the use of mixed fuels in the presence of a more viable forest stock. This finding suggests that households show fuel stacking behavior (Burke and Dundas, 2015; Shankar et al., 2020). Such behavior is often found when no single fuel can wholly meet every type of energy need by a particular household (Pillarisetti et al., 2019; Troncoso et al., 2019). We only find that fuel stacking behavior significantly reduces the probability of solely relying on clean energy (column 4, panel B of Table 3) for households that use firewood and are exposed to a higher forest stock. This finding is in line with Choumert-Nkolo et al. (2019), who document that households' probability of connecting to the electricity grid decreases with increasing fuel stacking in Tanzania. Investment costs related to the use of clean energy might explain this.

Table A.2 in the appendix shows the effects of other control variables in the main regression. More educated household heads use more clean energy, but the response is small: a 10% increase in education increases the likelihood of clean fuel consumption by 1% (column 1) to 2% (column 4). Previous research also points to a similar conclusion (Gebreegiabber et al., 2012; Heltberg, 2005). This is so because educated families have a high opportunity cost of time when using dirty energy (Heltberg, 2005). Education has a negative, albeit insignificant, impact on dirty fuel consumption, while earlier literature has shown a significant negative association between education and consumption of firewood (Gebreegiabber et al., 2012; Heltberg, 2005).

Higher wealth encourages mixed fuel use, see columns 3, 6, and 9 of Table A2, while clean fuel use is largely unaffected. In Uganda, the support for fuel stacking behavior therefore seems stronger than for the energy ladder hypothesis. Economic and sociocultural factors explain fuel stacking. Clean fuels have high initial investment costs, such as an electrical installation and purchase of its accessories (Choumert-Nkolo et al., 2019; Mazzone et al., 2021; Muller and Yan, 2018), high transaction costs (Maserà et al., 2000) and limited accessibility and reliability (Blimpo and Cosgrove-Davies, 2019; Guta, 2014; Kowsari and Zerriffi, 2011; Shankar et al., 2020). This motivates households to use mixed fuels as an insurance strategy (Louw et al., 2008). Culture (e.g., preferences, cooking patterns, food tastes, feeding habits, and firewood collection traditions) also drive fuel stacking. Households have different preferences for various fuels. For example, kerosene is the least preferred fuel in Ghana since it is time-consuming to use and has less power than firewood (Akpalu et al., 2011). Kenyan households cook firewood saving foods, such as tea and porridge, and githeri – a popular and nutritious food that ideally reduces eating frequency (Waswa et al., 2020). Also, food taste depends on fuel types used to cook it (Akpalu et al., 2011; Maserà et al., 2000; Shankar et al., 2020; Winther, 2007). Finally, fuel stacking, including firewood, prevails because firewood resources are mostly available (Cruz et al., 2020) and its collection is seen as an integral part of social life (Louw et al., 2008; Mazzone et al., 2021). The likelihood that mixed fuels could be adopted is significantly associated with female headship (Guta, 2012), family size, the number of rooms (Heltberg, 2005), the size of the land, and rainfall. However, the majority of these factors hinder the adoption of clean fuels.

5.2.2. Robustness checks

Our results are robust to a series of sensitivity checks. First, we conduct the same analysis as in Table 3 without using the terrain categories, mean temperature, mean rainfall, and region fixed-effects in Eq. (2). The resulting marginal effects of the estimates of forest status, reported in panels A to C of Appendix Table A.3, are almost similar in both magnitude and statistical significance to those reported in Table 3. Table S1 in the online supplementary material provides the results for other controls. Second, the EVI is treated as a continuous variable, different to the discrete variable levels used above. The EVI has a negative and weakly significant effect on using clean energy. The other magnitudes and statistical significances are otherwise similar to those in Table 3. The results indicate that increases in forest stock decrease the probability of using dirty energy according to the baseline definition (panel A of Table A.4) and firewood (panel B of Table A.4). The probability of choosing mixed fuels increases as shown in panels A to C of Table A.4. Results for additional controls can be found in Table S2 in the online supplementary material.

Third, we use separate random-effect probit models (REPM) for different fuel categories to evaluate the relationship between forest status and fuel choice. Table A.5 depicts the marginal effects estimated by FIMLE. The estimates are comparable to the main results reported in Table 3. The other controls for these models appear in Table S3 in the supplementary material. Fourth, we use the linear probability models (LPM) to show that the effect of forest conditions on energy choices is robust to the main results. Table A.6 presents these results, which are consistent with results reported above. The estimates for other controls can be found in Table S4 in the supplementary material. We finally analyze whether the role of forest stock (continuous form) in fuel choice varies between the rural and urban households, using separate regressions for the rural and urban sample as a fifth robustness check. The results are shown in panels A and B of Table A.7 for rural and urban households, respectively. The conclusions remain unchanged.

6. Conclusions and policy implications

Rural livelihoods depend on forests as a source of energy. Forests are also a key source of income, carbon sequestration and land protection, and are an integral part of day-to-day activities in many communities. This paper investigates the impact of forest status on households' fuel choice after controlling for other covariates. We use the Enhanced Vegetation Index (EVI) as an objective measure of forest status, and combine it with socioeconomic data from the Uganda National Panel Survey (UNPS) collected during 2009/10, 2010/11, and 2011/12. Households are assumed to choose between clean fuels (e.g., kerosene, LPG, solar energy, and electricity), and biobased dirty fuels (e.g., firewood, animal dung, crop residues, and charcoal), or a mix thereof.

The empirical results highlight some major findings. Compared to households in non-vegetated areas, households in sparsely and densely vegetated areas are substantially less likely to utilize dirty biobased fuels in general, and firewood and charcoal in particular. The effect on the use of firewood is bigger and more significant than the effect on the use of charcoal. The fact that charcoal is more commonly transported across regions and supplied on the market than firewood explains this result. The charcoal market is well integrated and more easier to purchase from the market compared to firewood. For example, charcoal traders often come from distant areas and employ agents in small trading centers to buy charcoal on their behalf (Tabuti et al., 2003).

The negative association between increases in forest stock and firewood use could potentially be explained by forest conservation efforts, implemented through legal restrictions, or stronger property rights, where both could support more viable forests while simultaneously reducing possibilities for firewood collection. Given the importance of firewood for households, this raises a concern that firewood collection in forests is overly restricted because of misguided forest protection policies, which might not achieve a sustainable balance between protection

¹⁴ These meals are intended to lower the daily cooking frequency.

and use of the forest resources. On the other hand, when access to forests is restricted, non-wood fuels (such as animal dung and crop residue) could replace firewood and even charcoal. Alternatively, households could adapt by increasing the use of exotic woody plants for firewood consumption. The potential for adaptation depends on the cultural and household level preferences for firewood plant characteristics and harvesting practices.

Improvements in forest biomass are associated with a higher likelihood of using mixed energy sources, i.e., increased fuel stacking behavior. The conclusion holds both when we treat all dirty fuels as a single basket, and for firewood and charcoal separately. Higher household wealth also increases the tendency to use mixed fuels. The literature provides multiple explanations for fuel stacking. For example, clean fuels are generally expensive and their supply is unreliable. Meles (2020) shows that there are frequent power disruptions, which reduces the benefits of having an electricity connection in Ethiopia. LPG cylinder deliveries are frequently late in Mexico, forcing households to wait until the next one or go to town to pick up a full cylinder (Masera et al., 2000). This makes the use of mixed fuels inevitable as a way of ensuring a constant supply of fuels at the household level. Cultural practices and behavioral factors could also motivate fuel stacking. Households use different fuels for cooking different foods because it is generally perceived that food tastes depend on the fuel used to cook the food. People may, for example, have preferences for foods cooked with firewood. In addition, attitudes towards the environment and intergenerational knowledge (e.g., the way someones' relatives cook food) affect fuel choice. These factors make fuel stacking, particularly with firewood use included, appealing. In contrast, the wealth coefficients do not provide strong statistical evidence for the energy ladder concept, i.e., the hypothesis that rising household income leads to a conversion from dirty to clean fuels. Higher wealth does significantly lower the use of dirty fuels, but it does not guarantee the switch to cleaner fuels.

Our results further show that household head education is positively associated with clean fuel adoption, while household head age, female-headed households, and family size are negatively correlated with clean fuel use. Larger livestock herds support the use of dirty fuels since it enhances access to animal dung. The use of mixed fuels is higher in female-headed households, households with more family members, and households with a larger number of rooms, while it is negatively related to the size of livestock. All results are on the overall robust to alternative model specifications and estimation strategies.

Our results have several policy implications. First, the lower possibilities for gathering firewood from protected and private forest areas underscores the necessity for alternative firewood supply, given that many people are still highly dependent on firewood. In this regard, encouraging households to grow early maturing trees could be useful as it would enhance the available firewood resources and ease the strain on the forest stock. Second, provision of modern cookstoves to households in sparsely and densely vegetated areas seems necessary to achieve the targeted access to clean energy sources and the targeted 40% decrease in wood usage aimed for by 2030. Policy makers should acknowledge the benefits associated with fuel stacking at the household level, as long as supply shortages temporarily constrain the use of different fuels. Third, increased access to education for household heads may be crucial for Uganda to reach its energy policy targets. This could be combined with campaigns to raise awareness about the importance of using clean fuels and managing forest resources sustainably. Fourth, policies that increase household wealth, e.g., through income diversification opportunities

and the provision of energy subsidies for the poor, can help in financing households' investments in clean energy. Fifth, the increased use of dirty fuels in response to larger livestock holdings could also be counteracted if households are encouraged to produce biogas using zero-grazing techniques. Such a transition is likely to require policies that take into account also local cultural practices related to livestock management. Sixth, when reliance on forest charcoal decreases due to restricted access to forests, policies need to secure a reliable supply of charcoal via proper trading routes and better functioning markets. The creation of charcoal cooperatives with local inhabitants serving on board membership might be beneficial.

Our study has several limitations that should be kept in mind. One is the lack of data on forest property rights, which prohibits us from identifying the role of these rights in forest status and energy choices. For example, using data from Thailand, Chankrajang (2019) reports that extensive community forestry leads to better forest cover. Moreover, our paper does not address the role of institutions, such as the level of democracy, and political accountability of forest authorities and community representatives, in forest status and the use of firewood and charcoal production, as argued by Nygren (2005) to be important for the relationship between the studied outcomes. In addition, the UNPS data on fuel expenditure, fuel quantities, and units for those, are mostly missing. The lack of such data prevent us from assessing the relationships between forest status, fuel choice, and households' energy intensity. Future surveys that include this information could help address these issues and thus provide more complete welfare estimates related to our research question.

CRedit authorship contribution statement

Bahre Gebru: Conceptualization, Data curation, Methodology, Formal analysis, Writing – original draft, reviewing and editing. **Katarina Eloffson:** Supervision, Conceptualization, Data curation, Methodology, Formal analysis, Writing – original draft, reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enpol.2022.113390>.

Appendix

Table A.1
Summary statistics of other controls.

	Year 2009/10		Year 2010/11		Year 2011/12		Pooled	
	Mean	N	Mean	N	Mean	N	Mean	N
Urban (=1 if yes)	.262	1955	.226	2077	.206	2238	.23	6270
Head age, years	45.927	1955	47.244	2077	47.396	2238	46.888	6270
Female head (=1 if yes)	.51	1955	.529	2077	.296	2238	.44	6270
Family size	6.554	1955	7.258	2077	7.78	2238	7.225	6270
Head education, years	5.52	1955	5.779	2077	5.467	2238	5.587	6270
Number of rooms	2.923	1955	8.733	2077	3.03	2238	4.886	6270
Land size, acres	4.672	1955	5.235	2077	3.571	2238	4.466	6270
Livestock size, TLU	359.651	1955	.844	2077	.781	2238	112.698	6270
Monthly consumption expenditure	286000	1955	235000	2077	227000	2238	248000	6270
Independent residence (=1 if yes)	0.293	1955	0.307	2077	0.316	2238	0.306	6270
Shared residence (=1 if yes)	0.570	1955	0.559	2077	0.552	2238	0.560	6270
Other residence (=1 if yes)	0.137	1955	0.134	2077	0.132	2238	0.134	6270
Plains (=1 if yes)	0.673	1955	0.695	2077	0.705	2238	0.691	6270
Plateaus (=1 if yes)	0.148	1955	0.125	2077	0.114	2238	0.128	6270
Mountains (=1 if yes)	0.179	1955	0.181	2077	0.181	2238	0.180	6270
Mean annual rainfall (mm)	1131.125	1955	1132.657	2077	1128.674	2238	1130.757	6270
Mean annual temperature (mm)	218.352	1955	219.054	2077	219.47	2238	218.983	6270
Central region (=1 if yes)	.332	1955	.303	2077	.282	2238	.304	6270
Northern region (=1 if yes)	.21	1955	.24	2077	.258	2238	.237	6270
Eastern region (=1 if yes)	.219	1955	.247	2077	.239	2238	.235	6270
Western region (=1 if yes)	.239	1955	.211	2077	.221	2238	.223	6270

Note: The analysis is at household-level. All figures in this table are nationally representative according to the UNPS. Consumption expenditure is monthly household expenditure in constant prices after adjusting for regional price variations measured in terms of Ugandan Shilling (UGX). TLU is Tropical Livestock Unit. 1USD ≈3533.80 UGX on August 2021.1 Acre ≈0.405 ha.

Table A.2

Marginal effects: the role of forest status in fuel choice (non-vegetated being the base category): other controls from Table 3.

Variables	Dependent variable: fuel choice								
	Panel A: Basket of dirty fuels			Panel B: Firewood used			Panel C: Charcoal used		
	Clean (1)	Dirty-I (2)	Mixed-I (3)	Clean (4)	Dirty-II (5)	Mixed-II (6)	Clean (7)	Dirty-III (8)	Mixed-III (9)
Urban	-0.000 (0.004)	-0.004 (0.010)	0.004 (0.012)	0.007* (0.004)	0.005 (0.012)	-0.011 (0.013)	-0.030*** (0.010)	0.003 (0.012)	0.027* (0.015)
Head age	-0.000*** (0.000)	0.000 (0.000)	0.000 (0.000)	-0.000*** (0.000)	0.000 (0.000)	0.000 (0.000)	-0.000 (0.000)	-0.001 (0.001)	0.001 (0.001)
Female head	-0.012*** (0.003)	-0.005 (0.005)	0.017*** (0.006)	-0.008** (0.003)	0.002 (0.006)	0.006 (0.007)	-0.037*** (0.010)	-0.019* (0.010)	0.056*** (0.013)
Family size	-0.024*** (0.003)	-0.016*** (0.006)	0.040*** (0.007)	-0.024*** (0.003)	-0.022*** (0.007)	0.046*** (0.008)	-0.061*** (0.010)	0.001 (0.010)	0.060*** (0.014)
Head education	0.001*** (0.000)	-0.000 (0.001)	-0.001 (0.001)	0.002*** (0.000)	-0.000 (0.001)	-0.002 (0.001)	0.001 (0.001)	-0.000 (0.001)	-0.001 (0.001)
Number of rooms	-0.008** (0.003)	-0.024*** (0.007)	0.032*** (0.008)	-0.010*** (0.004)	-0.017** (0.008)	0.027*** (0.009)	-0.017* (0.009)	-0.009 (0.012)	0.026* (0.014)
Land size	-0.004** (0.002)	-0.004 (0.003)	0.008* (0.004)	-0.006*** (0.002)	-0.001 (0.004)	0.007 (0.004)	-0.005 (0.004)	-0.004 (0.006)	0.009 (0.007)
TLU	0.002 (0.002)	0.010*** (0.004)	-0.013*** (0.004)	0.002 (0.002)	0.010** (0.004)	-0.012*** (0.004)	0.007 (0.007)	0.001 (0.008)	-0.008 (0.010)
Consumption expenses	-0.001 (0.002)	-0.013** (0.005)	0.013** (0.006)	0.001 (0.002)	-0.012** (0.006)	0.011* (0.006)	-0.014* (0.007)	-0.008 (0.008)	0.022** (0.010)
Shared residence	-0.001 (0.004)	0.001 (0.010)	0.000 (0.011)	0.007* (0.004)	-0.006 (0.016)	-0.001 (0.016)	-0.021* (0.011)	-0.006 (0.012)	0.027* (0.016)
Other residence	-0.012*** (0.004)	0.023*** (0.008)	-0.011 (0.009)	-0.014*** (0.005)	0.025*** (0.008)	-0.011 (0.009)	-0.023 (0.017)	-0.037 (0.025)	0.060** (0.027)
Plateaus	0.000 (0.004)	0.001 (0.008)	-0.001 (0.010)	-0.000 (0.004)	-0.001 (0.009)	0.001 (0.010)	0.004 (0.011)	0.016 (0.015)	-0.020 (0.016)
Mountains	0.007 (0.007)	0.004 (0.014)	-0.011 (0.016)	0.004 (0.007)	0.003 (0.014)	-0.008 (0.016)	0.030 (0.020)	0.003 (0.026)	-0.033 (0.030)
Mean rainfall	-0.000 (0.000)	-0.000*** (0.000)	0.000*** (0.000)	-0.000 (0.000)	-0.000*** (0.000)	0.000*** (0.000)	0.000 (0.000)	-0.000*** (0.000)	0.000** (0.000)
Mean temperature	0.000 (0.000)	0.001*** (0.000)	-0.001*** (0.000)	0.000 (0.000)	0.001*** (0.000)	-0.001*** (0.000)	0.000 (0.001)	0.001 (0.001)	-0.001 (0.001)
Observations	6270	6270	6270	5215	5215	5215	1834	1834	1834

Note: The dependent variable is whether or not the household chooses (a) at least one of the clean energy sources but not any dirty fuel inputs in columns 1, 4, and 7; (b) at least one of the dirty energy sources excluding any clean energy in column 2; (c) firewood as a dirty energy but not any other clean energy in column 5, and (d) charcoal as a dirty energy distinct from all clean energy sources in column 8 for cooking, lighting, and/or heating purposes. The definitions of mixed energy I to III in columns 3, 6, and 9 varies depending on the definitions of dirty energy I to III in each panel. The answers are coded as 1 if yes and 0 otherwise for each column in panels A to C. The authors apply IHSTA for land size, number of rooms, TLU, and head education. Monthly consumption expenditure and family size are in logarithmic forms. Rural, male headship, independent residence, and plain terrains are reference groups through out Table A.2. Columns 1–9 are REMNLM fitted with GSEM. Robust

standard errors clustered at the household level are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

Table A.3

Marginal effects: the role of forest status in fuel choice (non-vegetated being the base category): robustness check 1 excluding some explanatory variables.

Variables	Dependent variable: fuel choice								
	Panel A: Basket of dirty fuels			Panel B: Firewood used			Panel C: Charcoal used		
	Clean (1)	Dirty-I (2)	Mixed-I (3)	Clean (4)	Dirty-II (5)	Mixed-II (6)	Clean (7)	Dirty-III (8)	Mixed-III (9)
Sparsely vegetated	0.002 (0.005)	-0.056*** (0.012)	0.055*** (0.014)	-0.017*** (0.006)	-0.084*** (0.016)	0.102*** (0.018)	0.002 (0.016)	-0.027 (0.016)	0.024 (0.025)
Densely vegetated	-0.010* (0.005)	-0.087*** (0.014)	0.097*** (0.016)	-0.028*** (0.006)	-0.124*** (0.020)	0.152*** (0.022)	-0.024 (0.016)	-0.032** (0.015)	0.056** (0.023)
Latent variable, L		3.53e-16 (3.26e-16)	3.53e-16 (3.26e-16)		-3.19e-07 (9.60e-08)	-3.19e-07 (9.60e-08)		-1.37e-14 (8.98e-15)	
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region fixed-effects	No	No	No	No	No	No	No	No	No
Heterogeneity indicators									
Variance (L)		1.0 (constrained)			1.0 (constrained)			1.0 (constrained)	
Variance (equations)	0.582 (0.821)			0.430 (0.902)			1.66e-07*** (1.64e-08)		
Observations	6270	6270	6270	5215	5215	5215	1834	1834	1834

Note: The dependent variable is whether or not the household chooses (a) at least one of the clean energy sources but not any dirty fuel inputs in columns 1, 4, and 7; (b) at least one of the dirty energy sources excluding any clean energy in column 2; (c) firewood as a dirty energy but not any other clean energy in column 5, and (d) charcoal as a dirty energy distinct from all clean energy sources in column 8 for cooking, lighting, and/or heating purposes. The definitions of mixed energy I to III in columns 3, 6, and 9 varies depending on the definitions of dirty energy I to III in each panel. The answers are coded as 1 if yes and 0 otherwise for each column in panels A to C. Other controls appear in Table S1 in the online supplementary material. Columns 1–9 are REMNLM fitted with GSEM. Robust standard errors clustered at the household level are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

Table A.4

Marginal effects: the role of forest status in fuel choice: robustness check 2 using a continuous variable for forest status.

Variables	Dependent variable: fuel choice								
	Panel A: Basket of dirty fuels			Panel B: Firewood used			Panel C: Charcoal used		
	Clean (1)	Dirty-I (2)	Mixed-I (3)	Clean (4)	Dirty-II (5)	Mixed-II (6)	Clean (7)	Dirty-III (8)	Mixed-III (9)
EVI	-0.034* (0.019)	-0.376*** (0.058)	0.410*** (0.063)	-0.084*** (0.025)	-0.490*** (0.076)	0.574*** (0.082)	-0.104* (0.062)	-0.106 (0.067)	0.210** (0.085)
Latent variable, L		5.30e-17 (6.30e-16)	5.30e-17 (6.30e-16)		-1.18e-15*** (4.44e-16)	-1.18e-15*** (4.44e-16)		9.34e-07*** (5.88e-07)	9.34e-07*** (5.88e-07)
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Heterogeneity indicators									
Variance (L)		1.0 (constrained)			1.0 (constrained)			1.0 (constrained)	
Variance (equations)	9.38e-08*** (5.60e-09)			4.28e-08*** (2.88e-09)			13.845*** (4.428)		
Observations	6270	6270	6270	5215	5215	5215	1834	1834	1834

Note: The dependent variable is whether or not the household chooses (a) at least one of the clean energy sources but not any dirty fuel inputs in columns 1, 4, and 7; (b) at least one of the dirty energy sources excluding any clean energy in column 2; (c) firewood as a dirty energy but not any other clean energy in column 5, and (d) charcoal as a dirty energy distinct from all clean energy sources in column 8 for cooking, lighting, and/or heating purposes. The definitions of mixed energy I to III in columns 3, 6, and 9 varies depending on the definitions of dirty energy I to III in each panel. The answers are coded as 1 if yes and 0 otherwise for each column in panels A to C. Other controls appear in Table S2 in the supplementary material. Columns 1–9 are REMNLM fitted with GSEM. Robust standard errors clustered at the household level are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

Table A.5

Marginal effects: the role of forest status in fuel choice (non-vegetated being the base category): robustness check 3 using random-effect probit models for each fuel type.

Variables	Dependent variable: fuel choice				
	Clean (1)	Dirty (2)	Mixed (3)	Firewood (4)	Charcoal (5)
Sparsely vegetated	0.002 (0.007)	-0.092*** (0.016)	0.087*** (0.018)	-0.057*** (0.015)	-0.033 (0.026)
Densely vegetated	-0.003 (0.007)	-0.136*** (0.017)	0.136*** (0.019)	-0.100*** (0.016)	-0.020 (0.025)
Latent variable, L	-0.062** (0.031)	-0.189*** (0.458)	-0.065*** (0.003)	-0.116*** (0.025)	-0.229*** (0.009)
Other controls	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes
Region fixed-effects	Yes	Yes	Yes	Yes	Yes

(continued on next page)

Table A.5 (continued)

Variables	Dependent variable: fuel choice				
	Clean (1)	Dirty (2)	Mixed (3)	Firewood (4)	Charcoal (5)
Heterogeneity indicators					
Variance (L)	1.0 (constrained)	1.0 (constrained)	1.0 (constrained)	1.0 (constrained)	1.0 (constrained)
Variance (equations)	2.272*** (0.623)	1.476*** (0.239)	1.496*** (0.206)	1.649*** (0.256)	1.659*** (0.219)
Observations	6270	6270	6270	6270	6270

Note: The dependent variable is whether or not the household purely relies on clean energy sources (column 1), purely chooses dirty fuels (column 2) or depends on the mixtures of clean and dirty fuels (column 3) for cooking, lighting, and/or heating purposes. While the dependent variable in column 4 is whether or not the household chooses firewood as a dirty energy but not any other clean energy, column 5 asks whether charcoal is used as an energy source in the household. The answers are coded as 1 if yes and 0 otherwise. Other controls appear in Table S3 in the supplementary material. Columns 1–5 are REPM fitted with GSEM. Robust standard errors clustered at the household level are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

Table A.6

The role of forest status in fuel choice (non-vegetated being the base category): robustness check 4 using linear probability models for each fuel type.

Variables	Dependent variable: fuel choice				
	Clean (1)	Dirty (2)	Mixed (3)	Firewood (4)	Charcoal (5)
Sparsely vegetated	0.002 (0.013)	-0.108*** (0.021)	0.105*** (0.024)	-0.054*** (0.015)	-0.034 (0.025)
Densely vegetated	-0.003 (0.013)	-0.123*** (0.020)	0.126*** (0.023)	-0.069*** (0.012)	-0.018 (0.025)
Other controls	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes
Region fixed-effects	Yes	Yes	Yes	Yes	Yes
Observations	6270	6270	6270	6270	6270
R ²	0.095	0.197	0.181	0.229	0.490

Note: All regressions are linear probability models. The dependent variable is whether or not the household purely relies on clean energy sources (column 1), purely chooses dirty fuels (column 2) or depends on the mixtures of clean and dirty fuels (column 3) for cooking, lighting, and/or heating purposes. While the dependent variable in column 4 is whether or not the household chooses firewood as a dirty energy but not any other clean energy, column 5 asks whether the household uses charcoal as an energy source. The answers are coded as 1 if yes and 0 otherwise. Other controls appear in Table S4 in the supplementary material. Robust standard errors clustered at the household level are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

Table A.7

The effect of forest status on fuel choice: robustness check 5 for rural and urban households, and non-wood fuels.

Variables	Dependent variable: fuel choice						
	Clean (1)	Dirty (2)	Mixed (3)	Firewood (4)	Charcoal (5)	Animal dung (6)	Crop resid (7)
Panel A: Rural households							
EVI	-0.011 (0.044)	-1.935*** (0.160)	1.945*** (0.166)	-1.844*** (0.158)	-0.035 (0.119)		
Observations	4827	4827	4827	4827	4827		
Panel B: Urban households							
EVI	-0.007 (0.083)	-0.480*** (0.120)	0.486*** (0.140)	-0.228*** (0.081)	-0.120 (0.160)		
Observations	1443	1443	1443	1443	1443		
Panel C: Non-wood fuels							
Sparsely vegetated						0.003** (0.002)	0.034*** (0.011)
Densely vegetated						0.000 (0.001)	0.010 (0.007)
Common covariates							
Other controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Region fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Note: The dependent variable is whether a household uses the energy source indicated in the column heading in a given year for cooking, lighting, and/or heating purposes. All regressions are linear probability models. The forest status is continuous in panels A and B but categorical in panel C with non-vegetated as the reference category. The controls (not reported in the Appendix to save spaces) are household head's age in years, female head, family size, head education in years, number of rooms, land size, TLU, and monthly consumption expenses. The authors apply IHSTA for land size, number of rooms, TLU, and head education. Monthly consumption expenditure and family size are in logarithmic forms. Male headship is used as a reference category. Robust standard errors clustered at the household level are reported in parentheses. ***p < 0.01, **p < 0.05, *p < 0.1.

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This doctoral thesis examines how the scarcity of natural resources and climate change impacts households in Ethiopia and Uganda. Paper I explores the connection between precipitation variability and the selection of sanitation technologies. Paper II analyses how forest biomass availability influences fuel choices. Paper III investigates the impact of water scarcity on diarrheal incidence and individuals' decisions to buy health insurance. Paper IV scrutinizes the consequences of temperature increases on farm labor market outcomes.

Bahre Gebru Kiros received his PhD in Economics at the Department of Economics, Swedish University of Agricultural Sciences, Uppsala, Sweden. He earned an MSc in Economics from Addis Ababa University, Ethiopia, and a BA in Economics from Jimma University, Ethiopia.

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