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Fuel scarcity or household wealth? Assessing the drivers of cooking energy consumption patterns in rural areas in East Africa

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ABSTRACT

Rural households in Tanzania and Mozambique depend mainly on charcoal, firewood and other traditional fuels, such as cow dung or agriculture by-products, to cook. Simultaneously, fuel scarcity is an important phenomenon that leads households to apply coping strategies such as reducing the number of meals or increasing walking distance to collect firewood. Despite the well-known negative health, economic and potential ecologic impacts, the transition away from solid biomass energy sources is not expected in the short run. Thus, understanding the patterns of biomass energy consumption is essential to allow sustainable development in the household cooking sector. In this study, we evaluated the influence of wealth status and fuelwood scarcity on household energy choices in four villages with case study sites in Mozambique and Tanzania. The fuel usage patterns are consistent with the 'energy stacking' model as, despite an increase in the consumption of charcoal, firewood remains the principal cooking fuel. Wealth does not necessarily result in a transition toward cleaner fuels, nor does scarcity result in the use of other forms of traditional bioenergy. We suggest the promotion of fuel reduction strategies such as improved cookstoves or the implementation of on-farm trees to reduce the pressure on forests.

KEYWORDS

Energy transition; clean cooking; biomass-dependent households; Mozambique; Tanzania

1 Introduction

Recent estimates suggest that, unless rapid action is taken, one-third of the global population will still rely on charcoal, firewood, dung, and other traditional fuels to cook by 2030 (UN 2021). Currently, 77% of the global population without access to electricity – around 568 million – live in Sub-Saharan Africa (SSA) (IEA, IRENA, UNSD, World Bank, WHO

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2022). This has resulted in the highest average per capita wood fuel consumption in this region compared to the rest of the world (Iiyama et al. 2014). In general, poor rural residents may prefer the freely available wood fuels and spend their income on other priorities, especially those without free alternatives (Kar and Zerriffi 2018). Nevertheless, in addition to time poverty (Thorlakson and Neufeldt 2012) and the negative health and economic impacts (Fisher et al. 2021), the use of wood fuels can contribute to alter the vegetation structure (Luoga et al. 2002). While a rapid transition away from wood fuels cannot be expected due to several factors, including mismatches between cooking technologies and household needs, costs and unreliable supply of clean fuels (Shankar et al. 2020), the need to safeguard forest resources is urgent. In particular, deforestation and forest degradation have negative impacts on ecosystem services and rural livelihoods and are considered important contributors to greenhouse gas (GHG) emissions. Moreover, deforestation (also due to wood fuels/traditional fuels extraction) can, in turn, lead to wood fuel scarcity and reduced fuel consumption. This can have negative impacts, such as a reduced number of meals and increased walking distance to collect fuelwood (Scheid et al. 2019).

Tanzania and Mozambique are among the countries with the lowest rate of access to clean cooking fuels and technologies. On average, only 5% or less of the population had access between 2016 and 2020 (IEA, IRENA, UNSD, World Bank, WHO 2022) which sustains the dependence on biomass energy. This has been a concern for the governments and is perceived as an environmental problem. However, biomass provides energy for more than 80% of the population, therefore, attempts to regulate, reduce or ban biomass energy consumption have resulted in failure or illegal exploitation (Massuque et al. 2021). As such, in order to design appropriate strategies and derive suitable policies to overcome the negative effects of biomass energy consumption, it is necessary to investigate and understand the local specific contexts. Although some analyses indicate that wealthier households are more likely to use cleaner energy sources, whereas poor households primarily use solid fuels such as firewood and dung (Démurger and Fournier 2007; Baiyegunhi and Hassan 2014), the evidence is still mixed (Démurger and Fournier 2011), as others suggest that household wealth increase firewood and charcoal consumption (Shi et al. 2009; Guta 2014). Thus, poverty reduction may not necessarily be translated into clean energy consumption. In fact, household cooking fuel demand and consumption pattern is context-specific and vary widely over geographies (Ravindra et al. 2019). Nevertheless, their understanding is essential to allow sustainable development in SSA.

Johnsen (1999) suggests that fuel-transition prospects can only become realistic under the fuelwood scarcity scenario, an inevitable situation in Tanzania and Mozambique. Studies in both countries have shown that biomass energy consumption – especially charcoal – is accelerating deforestation and forest degradation (Mwampamba 2007; Sedano et al. 2021), reducing wood fuel availability. However, it is still unclear how it influences the dynamics and patterns of fuel consumption in rural areas. Evidence suggests that rural residents use a mix of fuels, including charcoal (Hoffmann et al. 2015), but the studies often do not account for the variables that determine the choice of fuels. Hence, we conducted a study to determine the influence of wealth status on household energy choice while controlling for other socioeconomic and demographic characteristics. We compared an area which faces fuelwood scarcity due to reduced forest cover to others with much greater forest coverage to analyse energy consumption patterns. We aim to understand to what extent rural household energy choices and consumption are linked to household wealth and fuelwood scarcity in Mozambique and Tanzania.

2 Methodology

2.1 Study design and sampling strategy

This study was undertaken within the framework of the Vegi-Leg Project (www.vegi-leg.org). In Mozambique, the study villages were Ruace and Macuarro, located in Gurue District, Zambézia Province. In Tanzania, the study villages were Mitumbati (Nachingwea District) and Mibure (Ruangwa District), situated in Lindi Region (Figure 1). The typical forest of the study case sites is dominated by miombo woodlands (Campbell 1996; Tarimo et al. 2015). These woodlands are dominated by trees from the genus *Brachystegia, Julbernadia* and *Isoberlinia* and offer various goods and services to the local communities, such as providing food and biomass energy, medicinal plants, etc. (Campbell 1996). The biomass energy is particularly important in our study villages since, in addition to cooking, it's used for warming water for hygiene, room heating, lighting and, in some cases, insect repellence. In this study, however, since these energy services are regularly combined with cooking, mainly in the three-stone fireplace, our questionnaire primarily focused on cooking energy. According to the records at the local administrative offices, population size in the Tanzanian villages, Mitumbati and Mibure, is 4850 people and 3080 people, respectively. The Mozambique villages, Ruace and Macuarro, have 5625 inhabitants and 3372

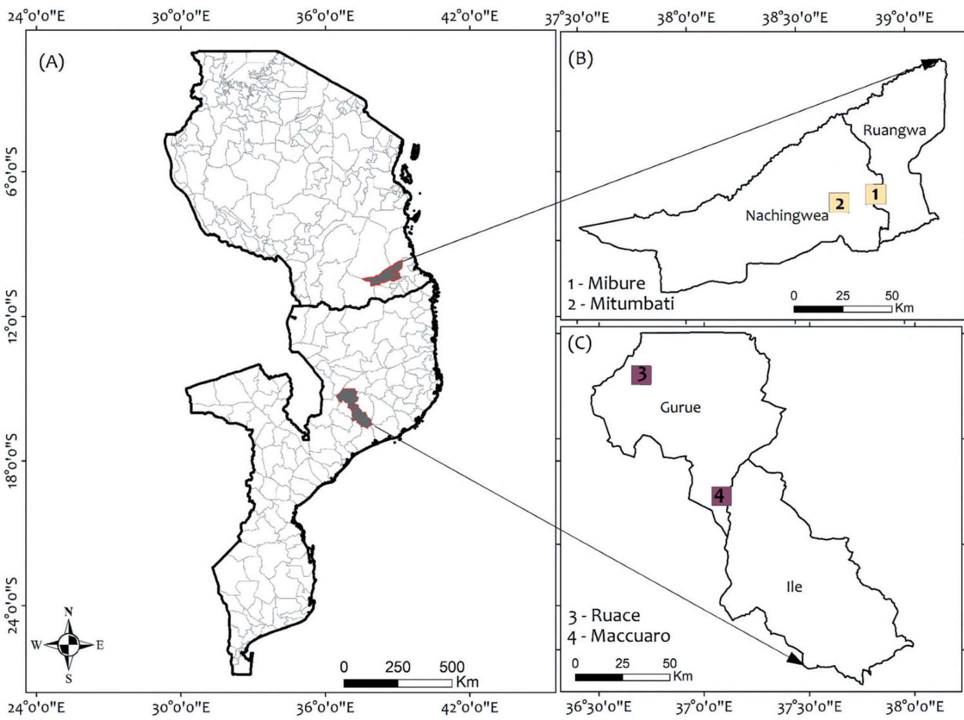

Figure 1. Study areas in Tanzania and Mozambique.

Table 1. Elevation, minimum and maximum temperatures in the study villages.

Village	Elevation (m above sea level)	Minimum Temperature (°C)	Maximum Temperature (°C)
Ruace MZ	612	12	35
Macuarro MZ	670	12	37
Mitumbati TZ	478	16	36
Mibure TZ	443	14	37

inhabitants, respectively. The primary common characteristic of these study villages is that they are mainly agriculture-based areas. Contrasting climatic and livelihood structures were also relevant considerations in selecting the respective study villages. Tanzania case-study villages are characterised by sub-humid climatic conditions with a prominent rain-fed maize-pigeon pea intercrop farming system integrating cashew as the major cash crop, while Mozambican study villages present humid climatic conditions with production systems characterised by a millet-pigeon pea farming system, with soybeans as the major cash crop. The elevation and temperatures for each study site are similar (Table 1). Ruace was used as a basis for comparison due to its much lower forest coverage and thus much larger fuelwood scarcity.

A sampling target of at least 220 households (HHs) for each study village was pre-determined. A stratified random sampling design was used to select study participants from a sampling frame of household heads lists provided by the respective village leaders and local administrative services. Stratified random sampling was achieved with an ad-hoc function in R-software with household head sex and hamlet of abode as strata. The selected sample thus reflected the strata proportions in the sampling frame. For each sampled household, both male and female respondents were interviewed together whenever possible (dual HHs). Where that was not possible, only a female or male respondent was interviewed from the household (single HHs). In Tanzania, 667 respondents from 442 randomly selected HHs (216 single HHs and 226 dual HHs) were ultimately interviewed. While in Mozambique, 861 respondents were interviewed (400 single and 461 dual HHs). The study was performed following the 'Declaration of Helsinki' guidelines and was ethically reviewed by the Mozambican National Committee of Bioethics in Health (IRB00002657, Ref 370/CNBS/19) and the Tanzanian National Institute for Medical Research and the Ministry of Health, Community Development, Gender, Elderly and Children in Dar es Salaam (NIMR/HQ/R.8a/Vol. IX/2226). The research objectives were explained to all participants, and an informed consent was subsequently obtained.

2.2 Land use and land cover composition of the study areas

Satellite images were used to derive the land cover maps for the study sites for 2019 (Figure 2). A subset of Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) satellite images for each site was downloaded and processed using a Google Earth Engine (GEE) script. GEE permits an automatic retrieval of archived satellite imageries and enables their analysis to be conducted on the server. We used blue, green, red, near-infrared, and normalized difference vegetation index bands from the already geometrically and radiometrically surface reflectance products to map the major land cover types common in the study sites (Figure 2). Accordingly, cropland, grassland, forest, water, roads, and settlements covering the study extents in each site were mapped, and their approximate coverage quantified. From the

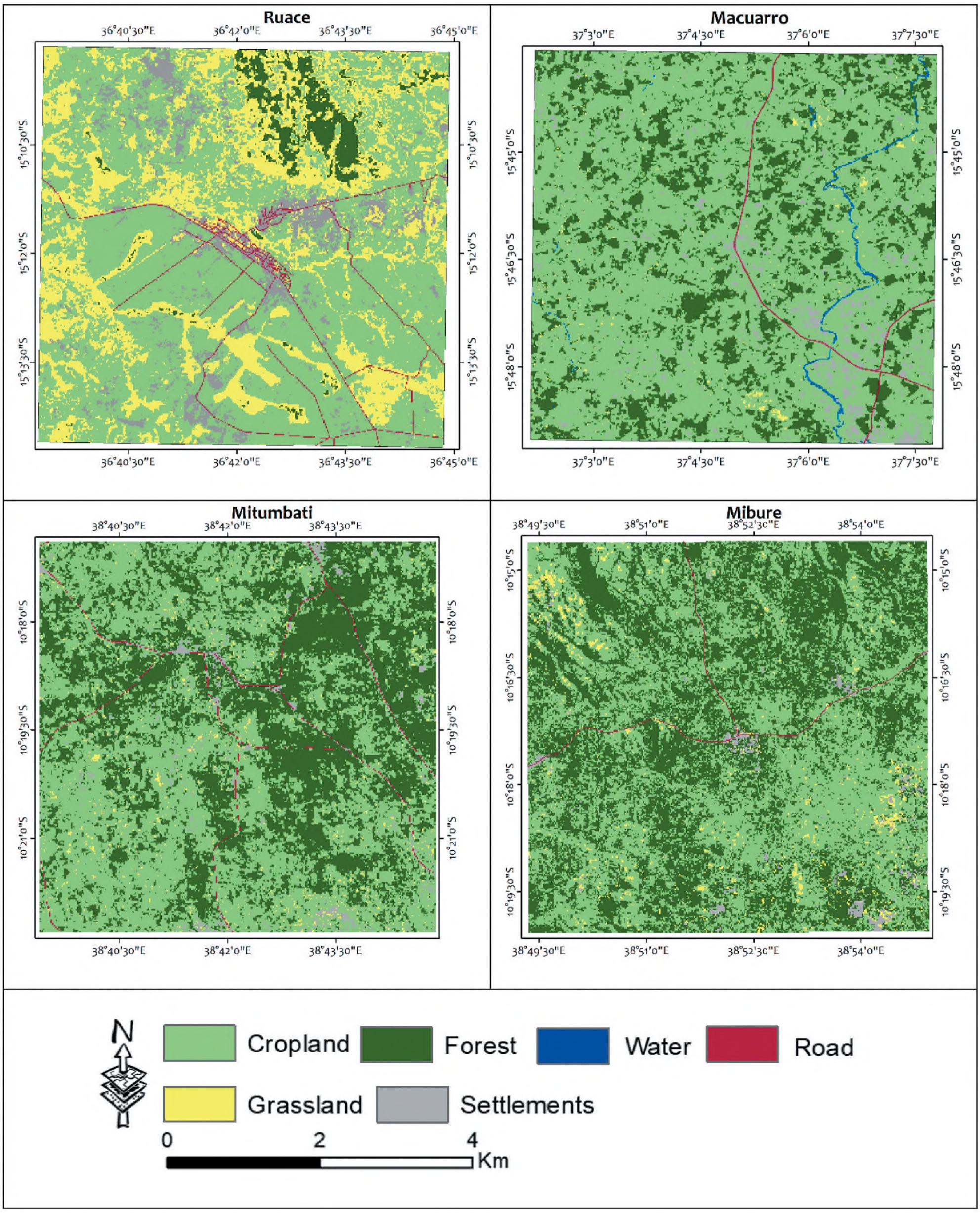

Figure 2. Land use and land cover composition.

centre point of each village, we defined a catchment area using a 5-kilometre buffer. Therefore, the final coverage considered for each village was an area of 100 km^2.

2.3 Household energy consumption and socioeconomic data collection

A structured questionnaire with English (for Tanzania) and corresponding Portuguese translations (for Mozambique) was administered to respondents between July and

August 2019 in local dialects across the study villages. The questionnaire comprised 10 sections, including two sections that were used in this study (see supplementary file: questionnaire) socioeconomic and demographic information (age of household head, occupation, education level, household size, etc.) and energy consumption (type and source of energy, weekly consumption, etc.).

Enumerators with at least a bachelor's degree and good comprehension of English (for Tanzania) or Portuguese (for Mozambique) and respective local dialects in the study villages were recruited and trained for at least two days about the administration of the study questionnaire. A pre-test of the questionnaire was also conducted before the actual fieldwork to ensure that the questions were understood by the respondents and elicited meaningful or desired responses. Mobile data collection applications (Kobo and Open Data Kit) were used to administer the questionnaire through face-to-face interviews with the respondents. Mobile data collection platforms minimise data entry errors and facilitate timely data aggregation.

2.4 Household wealth status

We measured each household's wealth status based on assets ownership and access to utility services and infrastructures. This was separately done for each of the countries to derive country-relevant wealth metrics. We used this approach since it is a better or more valid reflection of living standards and a more permanent status than, for example, monetary income or consumption (Rutstein and Johnson 2004). However, considering that the assets and household characteristics do not contribute equally to a household's wealth status, we applied principal components analysis (PCA) to create a factor weight associated with each variable in accordance with Vyas and Kumaranayake (2006). These weights represent the relative importance of each variable and were used to calculate a wealth index score for each household. PCA, a multivariate technique, is used to create an uncorrelated set of new orthogonal variables called principal components from an initial set of correlated variables. It can be represented as:

$$PC_m = \alpha_{m1}X_1 + \alpha_{m2}X_2 \ldots\ldots \alpha_{mn}X_n \tag{1}$$

Where PC is the principal component, α represents the weights and X the initial binary variables indicating assets ownership and access to utility services and infrastructures.

Descriptive statistics were used to select the variables used in PCA and the first principal component (PC_1) was used to calculate wealth indexes (Table 2). All variables with less than 10% and more than 90% of positive responses were removed, since PCA works best when the distribution of variables varies across households (Vyas and Kumaranayake 2006). This was done to avoid problems of clumping and 'truncation', which may occur if an insufficient number of asset indicators are used and if there are no indicators that allow differentiating between socioeconomic groups. For example, if many households do not own assets and have similar access to utilities and infrastructure, the distinction between the poor and the very poor, or between the rich and the upper middle class, would be difficult (McKenzie 2005; Vyas and Kumaranayake 2006). Cluster analysis was performed on the PCA-derived wealth indices to classify households into three wealth classes (i.e. low, medium and high) following Cortinovis et al.

Table 2. Household assets and utilities.

Variable	Ruace MZ (n = 407)		Macuarro MZ (n = 454)		Mitumbati TZ (n = 334)		Mibure TZ (n = 333)	
Assets ownership								
	Percentage	PC_1 (weight)	Percentage	PC_1 (weight)	Percentage	PC_1 (weight)	Percentage	PC_1 (weight)
Bicycle	74%	0.2188	48%	0.1527	85%	0.1923	78%	0.3144
TV	26%	0.4291	5%		12%	0.2608	6%	
Radio	29%	0.1979	36%	0.2233	45%	0.2421	43%	0.3136
Cellphone	0%		0%		62%	0.3256	57%	0.3274
Sewing machine	0%		0%		4%		1%	
Generator	1%		1%		0%		1%	
Tractor	0%		1%		0%		0%	
Tractor implements	2%		2%		0%		0%	
Oxen	1%		0%		1%		0%	
Ox implements	0%		0%		0%		0%	
Wheelbarrow	3%		0%		0%		0%	
Hand hoe	100%		96%		92%		95%	
Rake	0%		0%		27%	0.3134	30%	0.3532
Spade/shovel	0%		0%		25%	0.2851	27%	0.2813
Axe	0%		0%		65%	0.2019	66%	0.2999
Digging fork	0%		0%		10%	0.1802	9%	
Grain mill	81%	0.1079	92%		0%		0%	
Car	1%		2%		1%		0%	
Motor bicycle	19%	0.3433	9%		4%		12%	0.1935
Fridge	10%	0.3694	2%		0%		0%	
Cooking_stove	45%	0.3633	16%	0.2648	27%	0.177	22%	0.2735
Tables	68%	0.4195	40%	0.3836	65%	0.3212	73%	0.3858
Chairs	77%	0.356	53%	0.3547	68%	0.3151	69%	0.3315
Other assets	17%	0.0316	28%	0.1468	40%	0.079	50%	−0.0305
Utility services and infrastructures								
River, canal or surface water	2%		28%	−0.4088	1%		0%	
Public well or groundwater	64%	−0.091	44%	0.418	20%	0.1145	8%	
Private well or groundwater	20%	0.0012	51%	−0.4551	77%	−0.0932	16%	0.101
Public piped/tap drinking water	11%	0.0597	6%		1%		76%	0.1402
Private piped/tap drinking water	14%	0.124	2%		0%		0%	
Pit toilet/latrine	96%		89%	0.1145	74%	−0.3162	90%	
Flush toilet	1%		0%		24%	0.3404	7%	

(1993). A chi-square test of independence was applied to test the significance of the relationship between household wealth classes and the village of residence.

2.5 Fuel scarcity

We used the population size in each village, divided by the forest cover (in hectares) in the 100 km^2 area to obtain the number of people per hectare of forest. This index was used as a proxy measure of fuel scarcity. This approach resulted in a fuel scarcity index of 13.68 people/ha in Ruace, 0.68 people/ha in Mibure, 1.55 people/ha in Maccuaro and 1.15 people/ha in Mitumbati. As such, Ruace presented the highest fuel scarcity, whereas Mibure was the most fuel abundant area.

2.6 Factors affecting energy choice

A bivariate probit model was applied to analyse the effect of wealth status and fuel scarcity on the usage of the two main cooking energy types, firewood and charcoal, controlling for geographic location and size of the household, age, gender, occupation and education of the household head. The model can be expressed as:

$$y_j^* = \alpha_j + \beta_j X_j + u_j \quad j = 1, 2 \tag{2}$$

$$y_j = 1 if y_j^* > 0 \; and \; 0 \; otherwise \tag{3}$$

Where X_j represents the vectors of independent variables, u_j the regression errors, α_j and β_j are parameters to be estimated and y_j^* are the latent unobserved variables related to the observed binary indicators of energy choice (y_j). In a bivariate probit model, u_1 and u_2 have a bivariate Gaussian distribution with 0 means and variances of 1 and correlation coefficient ρ. We assumed that $\rho \neq 0$, thus, estimated the two equations jointly by maximizing the log-likelihood function:

$$L(\theta) = \sum_{i=1}^{n} y_{i1} y_{i2} \ln \pi_{i11}(\theta) + y_{i1}(1 - y_{i2}) \ln \pi_{i10}(\theta) + (1 - y_{i1}) y_{i2} \ln \pi_{i01}(\theta) + (1 - y_{i1})(1 - y_{i2}) \ln \pi_{i00}(\theta) \tag{4}$$

Where $\theta = (\theta_1, \theta_2, \rho)$, $\theta_1 = (\alpha_1, \beta_1)$, $\theta_2 = (\alpha_2, \beta_2)$. The probabilities underlying the four possible combinations of energy choices are given by:

$$\pi_{11}(\theta) = \Pr(y_1 = 1, y_2 = 1) = \Phi_2(\mu_1, \mu_2; \rho \tag{5}$$

$$\pi_{10}(\theta) = \Pr(y_1 = 1, y_2 = 0) = \Phi(\mu_1 \quad - \Phi_2(\mu_1, \mu_2; \rho) \tag{6}$$

$$\pi_{01}(\theta) = \Pr(y_1 = 0, y_2 = 1) = \Phi(\mu_2 \quad - \Phi_2(\mu_1, \mu_2; \rho) \tag{7}$$

$$\pi_{00}(\theta) = \Pr(y_1 = 0, y_2 = 0) = 1 - \Phi(\mu_1 \quad - \Phi(\mu_2 \quad + \Phi_2(\mu_1, \mu_2; \rho) \tag{8}$$

Where $\mu_i = \alpha_j + \beta_j X_j$ and Φ_2 is the bivariate standard normal distribution with 0 means and variances equal to 1. The command *biprobit* in Stata was used to fit the bivariate probit model.

3 Results

3.1 Wealth status

The classification of households into low, medium and high wealth status based on the cluster analysis approach is presented in Table 3. Based on a chi-square test of independence, there were significant differences across categories for all villages (p-value <0.01, χ^2 = 86.999). Macuarro has the highest proportion of households in the high-wealth category (37%), while the highest proportion of households in Miburre is within the low-wealth status (45%). The households in Mitumbati are evenly distributed across all the wealth categories, whereas Ruace presents the highest proportion of households in the medium-wealth status (48%).

Table 3. Proportion of households in low, medium and high wealth status.

Village	N	Low (%)	Medium (%)	High (%)
Ruace (Mozambique)	407	19	48	33
Macuarro (Mozambique)	454	38	25	37
Mitumbati (Tanzania)	334	36	32	32
Mibure (Tanzania)	333	45	26	29

3.2 Energy consumption

The results presented in Table 4 indicate that most households in all study areas use firewood for cooking. The use of electricity is almost non-existent, being observed only in Ruace (0.2%). Gas and solar energy were also almost non-existent and were only observed in Mitumbati, while paraffin was found used by a tiny proportion of households in the two villages of Tanzania (Mibure and Mitumbati). The use of charcoal was observed in all four villages, but the two Tanzanian village, Mibure and Mitumbati, had a high proportion of households using charcoal (15.9% and 30.5%, respectively), compared to Macuarro and Ruace (1.3% and 9.8%, respectively).

The forest is the most important source of energy (firewood) in all four villages (Table 5). Ruace, which showed the lowest use of the forest as a source of energy, had the highest proportion of households that buy cooking energy. These results also reveal that, although in small proportions, some households produce their own energy; in particular it is clear from figures shown in tables 4 and 5 that a substantial part of the charcoal users in the two Tanzanian villages produce their own charcoal.

3.3 Land cover analysis

The results from the land cover analysis showed that the study sites are characterized by varied coverage of different land cover types (Figure 2). The analysis revealed that forestland coverage in the two Tanzanian villages, Mibure and Mitumbati was the highest at 44% and 42%, respectively (Table 6). Maccuaro recorded a moderate forest cover (21%), whereas Ruace recorded a low coverage of forest cover (4%). In Macuarro, clusters of forest patches are relatively evenly distributed across the study site. In Ruace, forests are concentrated in the northern part of the study site, surrounded by grassland zones. Grassland and cropland

Table 4. Proportion of households according to the type of energy they use.

Village	Charcoal	Electricity	Firewood	Paraffin	Gas	Solar energy
Ruace MZ	9.8%	0.2%	89.9%	0.0%	0.0%	0.0%
Macuarro MZ	1.3%	0.0%	96.9%	0.0%	0.0%	0.0%
Mitumbati TZ	30.5%	0.0%	98.2%	0.3%	0.9%	0.3%
Mibure TZ	15.9%	0.0%	94.9%	0.3%	0.0%	0.0%

Table 5. Proportion of households according to where and how they source their energy.

Village	Forest	Own field	Buying
Ruace MZ	83%	3%	14%
Macuarro MZ	95%	2%	2%
Mitumbati TZ	93%	5%	8%
Mibure TZ	88%	7%	9%

Table 6. Land use land cover (LULC) statistics.

	Area							
	Ruace (MZ)		Maccuaro (MZ)		Mitumbati (TZ)		Mibure (TZ)	
LULC Type	Coverage (ha)	Percentage (%)	Coverage (ha)	Percentage (%)	Coverage (ha)	Percentage (%)	Coverage (ha)	Percentage (%)
Forestland	411.1	4.1	2169.3	21.6	4210.5	42	4529.2	44.1
Cropland	5992.3	59.2	7483.7	74.4	5473.7	54.7	5370.4	52.2
Grassland	2952.9	29.2	53.5	0.5	129.8	1.3	220.7	2.1
Settlements	766.0	7.6	282.6	2.8	200.0	2	159.8	1.6
Water features	0.4	0	67.2	0.7		0	0	0

covers dominate a larger part of the study site in Ruace. There is also a high concentration of settlements in the central region. The settlements are situated along the road networks, which is similar in the other study sites. Maccuaro recorded high coverage under cropland, followed by Ruace. The cropland coverage in Mitumbati and Mibure was almost equal.

Regarding the distributions, croplands are evenly distributed across Maccuaro. Croplands dominated the southern part of Ruace, whereas, in Mitumbati, the western part was under cropland cover. In Mibure, croplands are interspersed with forestlands, which together comprise the dominant land covers. Water features are found in Maccuaro and Ruace, but they cover only a small portion of the study sites.

3.4 Factors affecting household fuel choice

The results in Table 7 show that, after controlling other socioeconomic and demographic variables, the probability of using firewood significantly decreases with fuel scarcity and with household wealth status. Whereas the probability of using charcoal significantly increases with the wealth status. However, no significant relationship between the use of charcoal and fuel scarcity was found.

Other variables also affect the consumption of firewood and charcoal: the age of the household head and the size of the household significantly increases the probability of households using firewood, but decrease the probability of households using charcoal. Furthermore, self-employment significantly increases the likelihood of charcoal consumption.

4 Discussion

The paper provides results that show that household energy consumption and wealth status patterns differ across different villages. The majority of households in Ruace (Mozambique) are within the medium-wealth status, while in the other villages the majority fall within the low-wealth category. The use of charcoal for cooking is present in all villages but is more common in the two Tanzanian villages. Nevertheless, firewood is still used for cooking by 90% or more of the households in any of the 4 villages. The persistence of firewood use among households can be explained by the "fuel stacking" model by which new cooking technologies and fuels are added, but even the most traditional systems are rarely abandoned (Masera et al. 2000). Moreover, this might imply that the different fuels are not

Table 7. Bivariate probit model estimations.

Dependent variables	Independent variables	Coefficients	Std.Err.	p-values
Firewood consumpion	Fuel scarcity	−0.03859	0.010342	<0.001
	Gender of household head	0.245058	0.184233	0.183
	Age of household head	0.015991	0.00402	<0.001
	No education	0.320851	0.759976	0.673
	Primary school	0.337708	0.737246	0.647
	Secondary school	0.173215	0.744259	0.816
	Formal employment	−0.23647	0.554967	0.67
	Casual labour	0.050661	0.334683	0.88
	Business	−0.01266	0.262596	0.962
	Self employment	−0.21259	0.215327	0.323
	Size of the household	0.077213	0.02875	0.007
	Wealthscore	−0.18719	0.036577	<0.001
	constant	0.577459	0.752197	0.443
Charcoal consumption	Fuel scarcity	−0.01376	0.00911	0.131
	Gender of household head	0.091974	0.125872	0.465
	Age of household head	−0.01137	0.002999	<0.001
	No education	−0.43067	0.678918	0.526
	Primary school	−0.40672	0.664244	0.54
	Secondary school	−0.38417	0.670701	0.567
	Formal employment	−0.11313	0.551643	0.838
	Casual labour	0.321457	0.23918	0.179
	Business	0.216756	0.19924	0.277
	Self employment	0.725623	0.15842	<0.001
	Size of the household	−0.15322	0.023998	<0.001
	Wealthscore	0.257345	0.029597	<0.001
	_cons	0.284207	0.676976	0.675

Likelihood-ratio test of =0: chi-square = 230.163 pvalue = <0.001

viewed as fully interchangeable; instead, different dishes are associated with specific energy sources, e.g. charcoal for grilled fish and fuelwood for rice and vegetables.

The highest proportion of households that buy cooking energy is found in Ruace, where we also found by far the lowest forest coverage per inhabitant. This suggests that fuelwood scarcity due to a low forest cover is an important factor for household consumption patterns in rural areas (Figure 2). In line with this, Jewitt et al. (2020) suggest that when faced with unreliable access, households can shift away from their preferred fuels. Nevertheless, contrary to expectation, we did not observe a shift toward other forms of traditional bioenergy such as agricultural by-products and animal dung. In the other villages, a lower proportion of households buy their cooking fuel, probably due to higher fuelwood availability in the forests, since forest cover per inhabitant was much higher than in Ruace.

The relatively high proportion of households buying fuel in Mibure and Mitumbati, compared to Macuarro, is probably due to the use of charcoal. In fact, Table 4 suggests that the consumption of charcoal, which is generally bought, is higher in the two Tanzanian villages. Despite the fact that forest cover in the Tanzanian study regions is more important than that of the Mozambican study regions, the high use of locally produced charcoal can exacerbate deforestation and forest degradation since charcoal has been pointed out as one of the biggest contributors to deforestation and forest degradation. One way to avoid unsustainable wood extraction resulting in deforestation and forest degradation is to increase the efficiency of consumption, e.g. via the use of improved cooking stoves. Moreover, policies could focus on enhancing environmental sustainability of charcoal supply value chain by, for example, applying charcoal briquettes technology and enhance end-use efficiency (Guta 2014).

Our results indicated that both fuelwood scarcity and household wealth could influence the choice of energy type but not necessarily the transition to gas, paraffin, or other forms of energy since the levels of use of this forms of energy is below 1%. Very high levels of firewood use still prevailed, even in villages where the level of wealth is high. The transition that took place due to wealth was from firewood to charcoal and not towards cleaner energies. As such, transition away from biomass energy is not expected in the short run. Our results are in line with studies that suggest the reduction of individual household energy consumption by using energy-efficient equipment such as improved cookstoves, and better insulation strategies for households, i.e heat retention systems, as well increasing on-farm biomass and developing agroforestry systems (Ndayambaje and Mohren 2011; Matavel et al. 2022).

The influence of household assets need to be further understood since they play an important role in energy use and substitution (Guta 2014). Therefore, we suggest future studies to further explore the effect of poverty alleviation measures on the transition from fuelwood to household commercial energy such as gas and electricity. Another important aspect to cover in future studies is the effect of fuel scarcity on food security as suggested by Scheid et al. (2019).

A potential limitation of this study is the fact that the model used does not include other types of energy. Ideally, we could have applied a multivariate model to take into account other types of energy but the number of households using electricity, paraffin, gas and solar energy in our sample was below 1% (Table 4). This could introduce bias in our model, hence we chose to use a bivariate model. Nevertheless, the results in Table 4 provide evidence that the use of clean energy sources is still limited. A central implication is that the energy transition from biomass to cleaner energy sources must be preceded by an intermediate implementation of strategies to increase the efficiency and sustainability of biomass energy production and consumption.

5 Conclusion

The present study aimed at understanding household energy choices among biomass-dependent groups in rural study sites in Mozambique and Tanzania. We estimated the influence of fuel scarcity and the wealth status on cooking energy consumption pattern. We found that a larger household wealth does not necessarily lead to a shift toward a cleaner energy, but toward charcoal, a pollutant type of fuel. We also found that when fuel scarcity index (the forest cover relative to the population size) increases, the proportion of households using firewood decreases. However the fuel scarcity index has no significant impact on the use of charcoal. Household wealth can thus be a means to ensure energy security but not necessarily a behavioural change towards clean energy. Therefore, we suggest the promotion of energy-efficient equipment's to reduce individual household energy consumption and of on-farm biomass and agroforestry systems to increase available biomass supply.

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