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Assessing the Relationship between Fuel and Charcoal Prices in Uganda

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Abstract: Charcoal is a dominant energy source in urban areas of Uganda, and increases in retail prices in the past have led to social unrest. This paper assesses the relationship between charcoal and fuel prices to determine whether fuel prices influence the retail price of charcoal. We specify a transportation cost model for charcoal supply and derive the reduced-form equilibrium price function. We estimate an error-correction model for the equilibrium price with monthly data from July 2010 to January 2021 to determine whether there are long-term and/or short-term relationships between the retail and supply prices of charcoal and the prices of diesel and other fuel types. As the price data are integrated of orders zero and one, the autoregressive distributed lag (ARDL) bounds test is used. The results show that there is a long-term relationship (cointegration) between the retail price of charcoal and the supply price of charcoal and the price of kerosene, which is a substitute energy source for the end users. The prices of firewood and diesel are not statistically significant in the model. The long-term equation includes a positive trend, indicating that the retail price of charcoal is increasing more over time than implied by the supply price of charcoal and the price of kerosene. The increasing demand from a growing urban population and the reduced supply from deforestation are trends that will increase the equilibrium price of charcoal, as observed.

Keywords: charcoal; fuel; prices; cointegration; long-run equilibrium; Uganda

JEL Classification: O13; Q41; C22

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1. Introduction

Household decisions about the type of cooking fuel to use have important economic and environmental implications. At the household level, cooking fuel use is influenced by the availability of specific appliance types, the availability of supporting fuel, and the household utility associated with the various options. In addition to availability considerations, households are likely to choose a cooking option that is considered affordable or has a price in line with their budget allocations. In sub-Saharan African nations, the main fuel sources for cooking are firewood and charcoal, with charcoal dominating in urban areas (D'Agostino et al. 2015; Rose et al. 2022). Nzabona et al. (2021) reported that almost 80% of the households in Kampala, Uganda's capital, used charcoal for cooking. Households prefer charcoal for cooking, as it is often a cheaper and more dependable energy source than alternative options such as electricity, liquefied natural gas (LNG), and kerosene (Aarakit et al. 2021; D'Agostino et al. 2015; Doggart et al. 2020).

The "Walk-to-Work" protests in Uganda in 2011 were, at least in part, due to sharp increases in fuel and food prices (Mutyaba 2022). During this time, charcoal prices increased sharply. A common belief is that the increases in charcoal prices were and still are linked to the rise in diesel fuel prices. However, there are other factors that could also influence charcoal prices. Assessing which of these factors, if any, and to what extent they impact the retail price are important for understanding the price formation process and for the design of any policy interventions.

The motivation for this paper is the claim that increasing diesel fuel costs are driving increases in retail charcoal prices. Generally, the prices of goods traded in markets are affected by both demand- and supply-side factors, including transportation costs. Therefore, an increase in the retail price of charcoal could be attributed to increased transportation costs as a result of either increased fuel costs or increased transportation distances due to deforestation and/or land-use conversions. Prices along spatially distributed supply chains are expected to obey a weak law of one price (Fackler and Goodwin 2001; Huffaker et al. 2021), where price differences reflect transportation and transaction costs and market conditions (Acosta et al. 2021).

This article assesses the relationship between charcoal prices and fuel prices to determine whether fuel prices influence the retail price of charcoal. The availability of suitable data for the empirical analysis of price transmission and market integration is generally a challenge (Barrett 1996; von Cramon-Taubadel 2017). Using monthly price data for the period from July 2010 to January 2021 for charcoal at different locations along the supply chain, we empirically test whether there are long-term and/or short-term relationships between charcoal prices and the prices of diesel and other fuel types using an error-correction model.

The role of charcoal as an energy source and as a contributing factor to deforestation has been widely researched (Branch et al. 2022; Chidumayo and Gumbo 2013; Masera et al. 2015). Although there are studies investigating the supply and value chains of charcoal (Agbugba and Obi 2013; Agyei et al. 2018; Khundi et al. 2011; Schure et al. 2013; Shively et al. 2010; Worku et al. 2021), these articles, except for one, do not explicitly address any of the factors that influence charcoal prices. Agbugba and Obi (2013) used daily prices for a single month to assess price transmission among supply, wholesale, and retail levels in Nigeria. Their analysis was short-term and did not include any external cost factors such as fuel prices. Thus, this paper adds novel empirical insights into price formation and price linkages in the charcoal supply chain.

This paper continues with a review of the literature in Section 2. Section 3 first describes the charcoal supply chain in Uganda and then presents a theoretical land-rent model for the price of charcoal in a central market. The data, data sources, and autoregressive distributed lag (ARDL) model are described in Section 4. The results are presented and discussed in Section 5, and Section 6 concludes this paper.

2. Literature Review

The published literature on charcoal, or, more broadly, woodfuel, has focused on three areas: (i) the environmental impact and sustainability of production (Chidumayo and Gumbo 2013; Mensah et al. 2022), (ii) the livelihood and poverty of producers (Brobbey et al. 2019; Khundi et al. 2011), and (iii) the usage of charcoal, including poverty and health issues, and households' choice of fuel, or type of energy, especially for cooking (D'Agostino et al. 2015; Doggart et al. 2020; Nzabona et al. 2021; Poblete-Cazenave and Pachauri 2018). Arnold et al. (2006) provided a broad overview of the literature on the woodfuel situation in developing countries. Rose et al. (2022) analyzed the current demand for charcoal in sub-Saharan Africa, and their forecasts indicated that strong urban growth will maintain charcoal use at high levels for decades. Mensah et al. (2022) reviewed charcoal production in the same area and raised concerns about how an informal sector based on small-scale production using inefficient technologies can meet the increasing demand for charcoal.

The literature on charcoal production, consumption, and prices is predominantly descriptive and often not based on formal empirical analysis. A recent comprehensive review of the published literature on charcoal in Tanzania by Nyamoga and Solberg (2019) was instructive. The authors identified 42 studies that deal with the production and consumption of charcoal; however, only six of these studies included statistical analyzes. Of these six studies, only four stated an explicit behavioral model for producers or consumers. Three of these studies investigated the determinants of charcoal consumption (D'Agostino et al. 2015;

Hosier and Kipondya 1993; Nyamoga et al. 2022), whereas Monela et al. (2007) investigated the socioeconomic factors that influence charcoal production decisions. However, none of these studies investigated market integration or price transmission along the supply chain.

Charcoal supply chains have been described and analyzed in several countries, including Uganda (Shively et al. 2010), Nigeria (Agbugba and Obi 2013), Mozambique (Baumert et al. 2016), Ghana (Agyei et al. 2018), and Ethiopia (Worku et al. 2021). Schure et al. (2013) studied supply chains in Central and West Africa. These studies are informative with respect to the organization and functioning of the supply chain, including the distribution of profit along the supply chain.

Agbugba and Obi (2013) collected prices on a daily basis for a single month from charcoal producers, wholesale agents, and retailers in the Abia State of Nigeria. Granger causality tests showed that there is a positive influence of the producer's price on the wholesale price but not the other way around. Furthermore, there is a bilateral relationship between wholesale and retail prices.

Using survey data obtained from charcoal producing households in the Amhara region of Ethiopia, Worku et al. (2021) estimated a linear regression model with the market supply of charcoal as the dependent variable, and household characteristics, the distance to the market, and the price paid to producers as the explanatory variables. They found a positive relationship between the quantity supplied and the price but no relationship between the quantity and the distance to the market. The relationship between the price and distance to the market was not analyzed.

In contrast to Worku et al. (2021), Hofstad and Sankhayan (1999) and Sankhayan and Hofstad (2000), informed by economic theory, used regression models with local charcoal prices as the dependent variable and the linear distance to the central marketplace as the single regressor. They found a clear negative relationship between the distance to the market and the price of charcoal in both Tanzania and Uganda.

Nyamoga and Solberg (2019) concluded that much of the reviewed literature on charcoal production and consumption lacks clear behavioral models and testable hypotheses. The studies by Hofstad (1997) and Sankhayan and Hofstad (2000) are exceptions, as they are based on an economic model of land rent (Randall and Castle 1985). This lack of theoretical foundation in the charcoal literature is in contrast to the literature on market integration and price transmission along supply chains, which has a strong price theoretic foundation (Fackler and Goodwin 2001; McNew 1996; von Cramon-Taubadel 2017). The study of spatial and temporal price relationships has a long history in agricultural economics (Barrett 1996; Takayama and Judge 1971; von Cramon-Taubadel 2017)[1] and remains an active research area, with recent examples exploring spatial market integration in the EU (Roman and Žáková Kroupová 2022) and price transmission in international markets under trade wars (Barboza Martignone et al. 2022).

3. The Charcoal Sector

3.1. Energy in Uganda

The population of Uganda was about 41 million in 2021. Approximately 90% of the total energy supply in 2021, amounting to 22 million tonnes of oil equivalent, was bioenergy, mainly wood and charcoal (IEA 2023). Almost 2% of the energy came from electricity, 80% of which is produced by hydroelectric power plants. Imported oil products, mostly petrol and diesel for transportation, represented nearly 9% of the total energy supply. About 6% of imported oil products were kerosene for household use. In 2022, electricity access was limited to about 19% of the population with on-grid access and 38% with off-grid access (MEMD 2023). Although the access rate to electricity has increased from 5% in 2002, electricity security in Uganda remains low (Wabukala et al. 2022).

In Uganda, as in most sub-Saharan African countries, the primary energy sources for cooking are charcoal and firewood. Charcoal is the dominant energy source (65.7%) for cooking in urban areas (MEMD 2016). In Kampala, the dominance of charcoal is even greater at 77.8% (Nzabona et al. 2021). A recent study found that energy poverty is widespread in Uganda, although with important geographical and social differences (Ssennono et al. 2021). The authors included the cost of charcoal as one of the factors in their assessment of energy poverty.

3.2. The Charcoal Supply Chain

A charcoal supply chain typically includes these key steps: production, transportation, wholesale, retail, and consumption, with different economic entities engaged in the different stages (Baumert et al. 2016; Sander et al. 2013). According to Shively et al. (2010), Uganda's charcoal value chain consists of producers, agents, traders, transporters, retailers, and consumers. Agents act as intermediaries between producers and wholesale traders and earn commissions for connecting producers with traders. Wholesale traders purchase charcoal through agents or directly from producers and sell it to retailers but do not sell charcoal directly to consumers.

As most of Uganda's charcoal production takes place on private land, production falls under the jurisdiction of the District Forest Services. Following a major forest sector decentralization reform in 2003, the District Forest Services has been responsible for monitoring and enforcing rules related to charcoal production on private land. The District Forest Services also play an important role in regulating the transport of charcoal beyond district boundaries. Charcoal production is carried out primarily on a small scale, involving a large number of producers. Shively et al. (2010) noted the inadequate capacity of the District Forest Services to monitor and enforce regulations on charcoal production. Instead of using charcoal production licenses as a means to collect revenues, districts rely on loading fees or taxes levied at the transportation stage in the value chain.

The main marketplace for charcoal is the city of Kampala (MEMD 2016). Transportation takes place along a few main roads leading into the city. Production is spread out, and its specific location depends on the availability of suitable forest species, manpower, and transportation possibilities.

3.3. Price Formation

We can use land-rent theory (Alonso 1964; Randall and Castle 1985) in the tradition of von Thünen to conceptualize the formation of prices along the value chain of charcoal from remote producers to the central marketplace of Kampala. The simplified theoretical model in this research tradition is of a long narrow city with a central business district (or marketplace). The model can be extended to a spatial equilibrium model (Fujita 1989). Hofstad (1997) used a spatial and dynamic land-use model to analyze the distribution of charcoal production around the city of Dar es Salaam.

Consider a central marketplace where charcoal is sold. Emanating from the marketplace is a road along which charcoal is produced. Charcoal is produced with a commonly known technology at a unit cost c_p. Charcoal is transported to the central marketplace by trucks. Assume that the transport business is competitive with unit costs tx, where x is the distance from the producer to the market, and t are the costs per unit of distance. Let c_m be the wholesale and retail transaction costs associated with the local and central markets. These costs can include loading fees, transport, and council taxes, as well as any payments necessary to operate in the central market. In equilibrium, the marginal unit of charcoal is produced at the location x_m, and the marginal producer at this location is paid c_p, that is, a price equal to the cost of production.

Producers of charcoal closer to the marketplace than the marginal producer earn a locational rent, as the roadside supply price at location $x < x_m$ follows the price gradient, $p(x)$, defined by the difference in transportation cost

$$p(x) = t(x_m - x) + c_p. \tag{1}$$

Let p^c denote the central market price of charcoal in a competitive situation. This price is equal to the marginal cost of providing this unit in the marketplace, that is,

$$p^c = c_m + tx_m + c_p. \tag{2}$$

Assuming a uniform distribution of charcoal production along the road, the aggregate quantity produced is:

$$q^s = \mu(x_m - x_u) \tag{3}$$

where x_u is the limit of how far away from the marketplace the urban (or agricultural) area extends, and μ is the supply of charcoal per distance unit. If charcoal production is not evenly distributed along the road, the supply at distance x could be given a supply density function $h(x) \geq 0$, and the aggregate supply would be the integral of the supply density from x_u to x_m.

Let the aggregate demand function for charcoal in the central marketplace be

$$q^d = d(p^c, z^d) \tag{4}$$

where z^d is one or more exogenous demand shifters.

In market equilibrium, $q^s = q^d$. By combining Equations (2)–(4), we can solve for the location of the marginal producer (x_m) as a function of external factors. Substituting this location into the market price Equation (2) yields the reduced-form price equation as:

$$p^c = f(t, z^d, c_p, x_u, \mu) \tag{5}$$

where transaction costs, c_m, are kept constant.

Following the analysis by Randall and Castle (1985), an increase in the demand for charcoal increases the central market price p^c, increases the distance to the marginal producer, and shifts the roadside price gradient in Equation (1) outward. Consequently, the average price along the road also increases.

An increase in fuel prices increases transport costs t. This leads to an increase in the central market price, and the location of the marginal producer becomes closer to the market. Additionally, the roadside price gradient becomes steeper, and the average roadside price increases. A reduction in available charcoal, say, due to deforestation, shifts the marginal producer farther away from the market, resulting in a higher market price, with all other factors constant.

The final price in the central marketplace is influenced by other factors beyond those included in this transportation cost model. For example, on the demand side, kerosene is a possible substitute for charcoal, as it is used in small fire stoves not only for cooking but also for lighting. Firewood is another possible substitute fuel source. Although firewood is mainly used in rural areas and not in urban areas, it can compete for limited resources in the production of charcoal. If firewood and charcoal are more likely to be actual substitutes in rural areas, there could be linkages between firewood prices and the supply price of charcoal. Olabisi et al. (2019) found evidence of substitution between charcoal and kerosene in Tanzania.

A detailed empirical analysis of the formation of prices along the charcoal value chain, with a credible assessment of the causal effects of population growth and deforestation on the retail price of charcoal, would require a structural econometric model estimated using spatial time-series data in combination with forest inventory data. However, quantity data are not available, nor are population or forest data. Instead, with access to only price data, we use the reduced-form price function in Equation (5) and other econometric methods based on cointegration to investigate whether there are any long-term relationships that influence retail charcoal prices (McNew 1996; Rapsomanikis et al. 2006).

4. Data and Methods

4.1. Data Sources

The Uganda Bureau of Statistics (UBOS) collects detailed price statistics on a monthly basis for a number of goods to support the calculation of their consumer price index. Here, we use disaggregated UBOS price data for the period from July 2010 to January 2021 for diesel (p^d), kerosene (p^k), firewood (p^f), and charcoal. The average price of charcoal collected in different markets in Kampala is used to represent the price of charcoal in the central market, denoted as p^c. UBOS also collects charcoal prices in the cities of Arua, Kabarole, Gulu, and Jinja. These markets are in charcoal-producing areas or along key transportation routes (Haysome et al. 2021). Thus, these prices are used to represent the supply price of charcoal, denoted as p^s. The definitions of the price variables are summarized in Table 1.

Table 1. Price variables constructed from Uganda Bureau of Statistics consumer price index surveys.

Symbol	Name	Unit	Geographical Area
p^c	Charcoal	kg	Kampala
p^f	Firewood	kg	Uganda
p^k	Kerosene	liter	Uganda
p^d	Diesel	liter	Uganda
p^s	Supply	kg	Arua, Kabarole, Gulu, Jinja

Accurate and up-to-date population numbers for Uganda are not available. A commonly used source for population data is the World Urbanization Prospects of the United Nations. This source provides estimates and projections for major urban centers around the world, including Kampala. However, these population numbers represent population estimates every five years, and any interpolation of these numbers on an annual scale resulted in a smooth annual population growth of approximately 5% over the 2010–2021 period, as can be seen in Figure 1, which shows projections and interpolations from the World Population Review.[2]

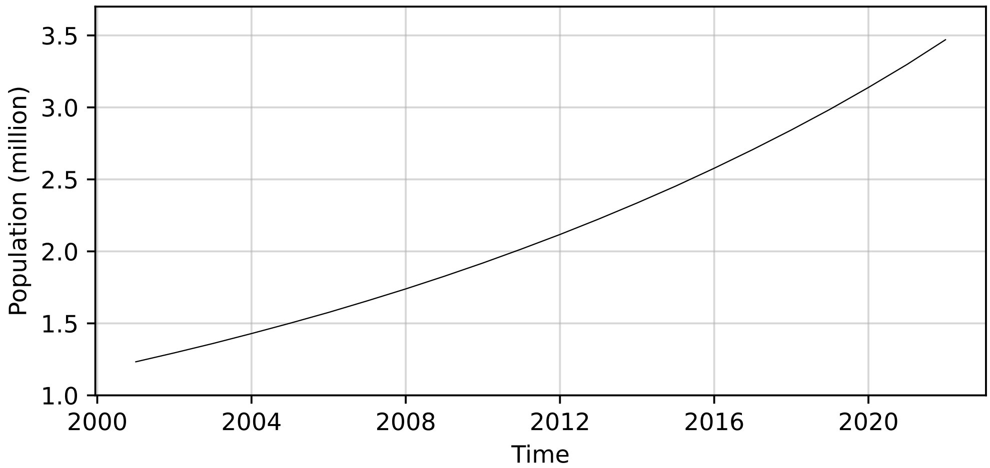

Figure 1. Population in the larger Kampala area (in millions). Estimates and projections from the World Population Review. Source: World Population Review (https://worldpopulationreview.com/, accessed on 13 June 2023).

The Global Forest Watch project[3] collects data and provides assessments of the extent of tree cover loss in a number of countries. The estimated area covered by forest in Uganda is shown in Figure 2. There is a fairly steady downward trend in forest cover. Increasing demand, everything else constant, intensifies tree harvesting and expands the harvested area (Hofstad 1997). The managed forest has a changing tree cover throughout the rotation period, and this is recorded as a period lacking tree cover following harvest. Forest cover could act as a proxy for the availability of raw materials for charcoal production.

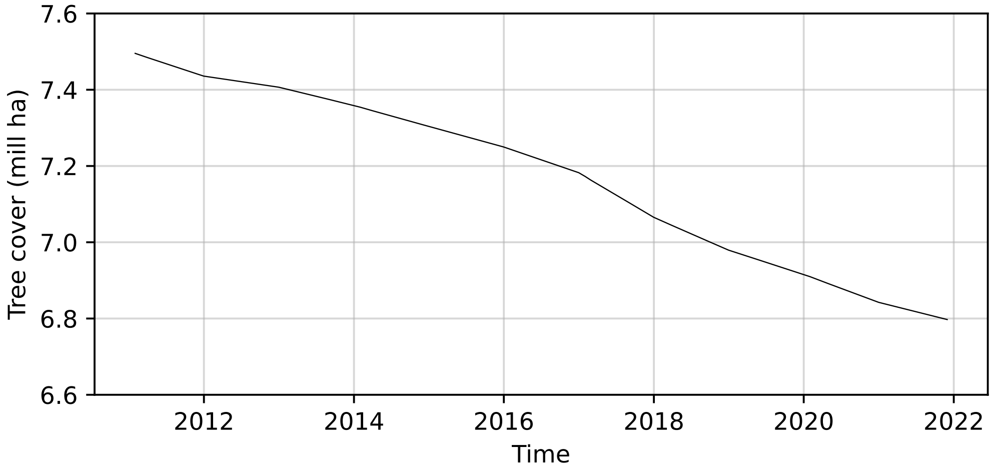

Figure 2. Total land area covered by forest in Uganda (in millions of hectares). Estimates from Global Forest Watch. Source: Global Forest Watch (https://www.globalforestwatch.org/, accessed on 13 June 2023).

However, as both the population size and forest cover are estimates and projections available at a coarser time scale than the price data, both series would need to be interpolated to match the time scale of the price data. The interpolated series would have long periods with constant change, containing little information and possibly causing multicollinearity problems if the series are differentiated. Instead of using estimated population and forest cover variables, these variables are replaced with a trend variable in the empirical analysis. This trend variable represents, on the one hand, the increase in demand as a result of population growth in the Kampala market, and, on the other hand, the effect, if any, of reduced supply due to deforestation and increased transportation distances.

4.2. Summary Statistics

The time paths for the nominal prices are shown in Figure 3. Charcoal prices (top panel) increased sharply in the period July–September 2011. The other price series show a similar pattern, although with a more gradual increase over a longer period. Both diesel and kerosene experienced price increases in the period 2016–2018. Nominal charcoal prices were fairly stable from late 2011 to late 2017 and then increased until 2020.

Adjusting for inflation in the period using the UBOS consumer price index (CPI), we can see from Figure 4 a decrease in real terms for both diesel and kerosene prices from 2011 to 2017. The increase in real charcoal prices from late 2017 coincides with an increase in real diesel prices. Real prices for firewood and supply charcoal do not show a discernible trend, but there is a noticeable jump in late 2011.

Table 2 presents the summary statistics for the real prices measured in real 2021 Ugandan Shilling (UGX). The correlation matrix for real prices is shown in Table 3. The market price of charcoal in Kampala has a positive correlation with the supply price of charcoal (0.638). This positive correlation between essentially the same product is to be expected in two different places along the supply chain. There is also a clear negative correlation between the market price of charcoal and the price of diesel (−0.513), which is somewhat surprising given the initial concern that increasing charcoal prices may have been driven by higher fuel costs in the transportation sector. There is a very high positive correlation between diesel and kerosene (0.957). These two products are based on crude oil and are both imported, and the high correlation coefficient reflects this.

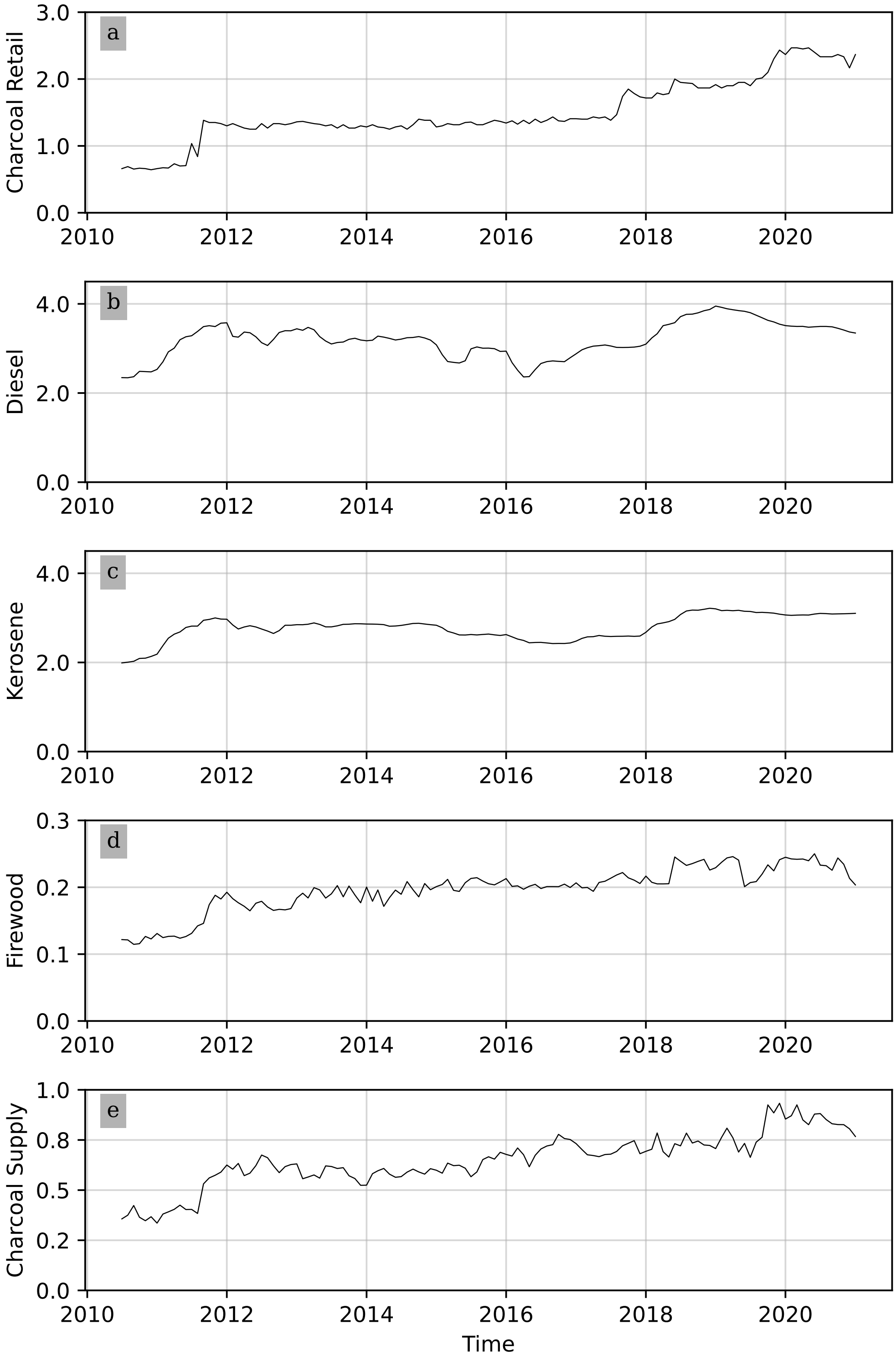

Figure 3. Nominal prices for different energy types (in thousands of UGX). (**a**) Charcoal retail price, (**b**) diesel price, (**c**) kerosene price, (**d**) firewood price, and (**e**) supply price for charcoal.

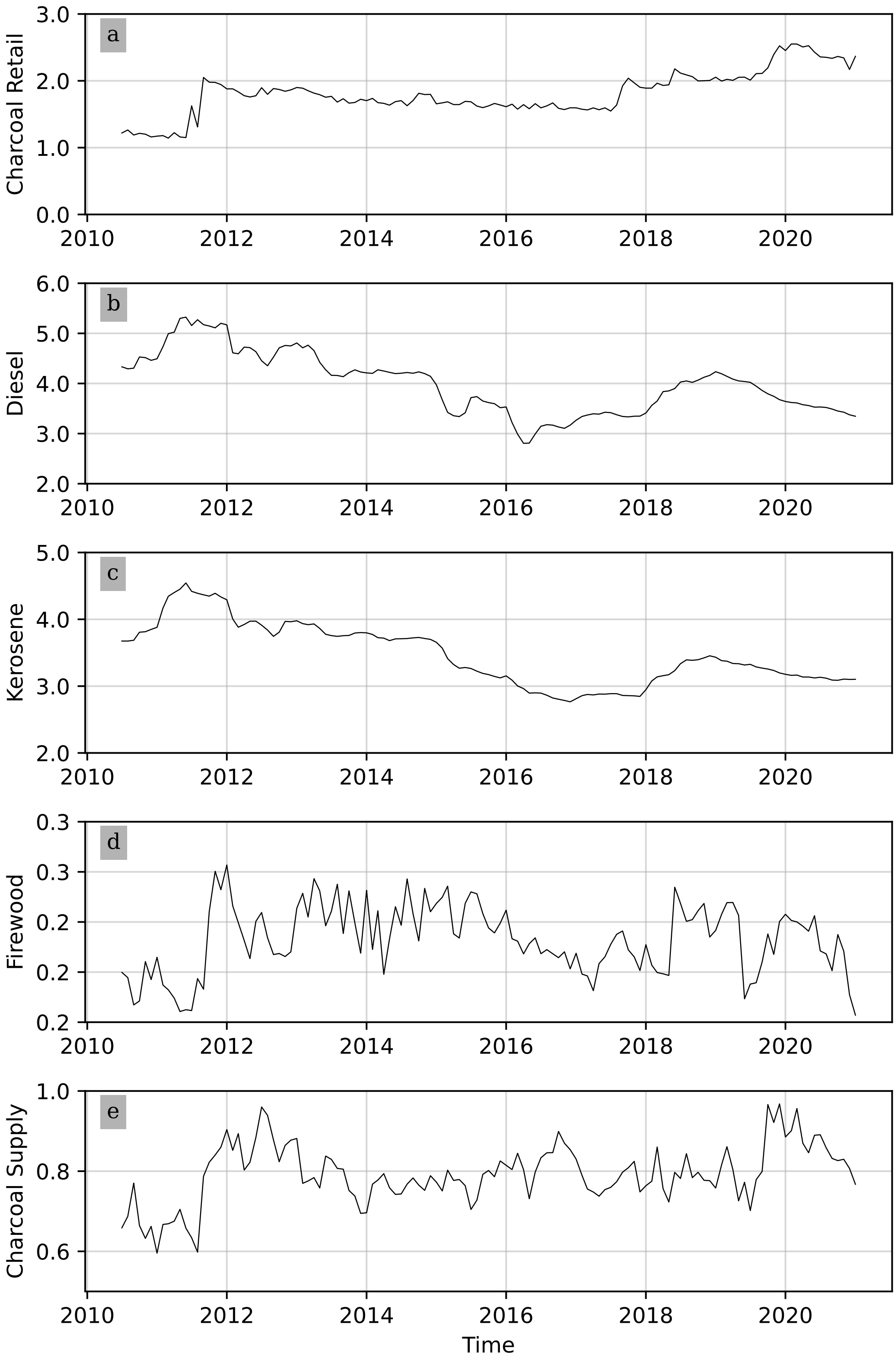

Figure 4. Real prices for different energy types (in thousands of UGX). Deflated with CPI to 2021 values. (**a**) Charcoal retail price, (**b**) diesel price, (**c**) kerosene price, (**d**) firewood price, and (**e**) supply price for charcoal.

Table 2. Summary statistics for energy prices in real UGX (2021 prices). $n = 127$.

Variable	Symbol	Mean	Std. Dev.	Minimum	Maximum
Charcoal	p^c	1808.05	327.15	1142.84	2551.47
Diesel	p^d	3995.82	606.42	2805.42	5323.67
Kerosene	p^k	3472.11	461.25	2765.24	4544.29
Firewood	p^f	241.54	17.03	203.51	278.42
Supply	p^s	792.74	73.72	595.60	967.74

Table 3. Correlation matrix for energy prices in real UGX. $n = 127$.

Variable	Charcoal	Diesel	Kerosene	Firewood
Diesel	−0.232			
Kerosene	−0.305	0.957		
Firewood	0.272	0.030	0.068	
Supply	0.638	−0.249	−0.271	0.330

4.3. Unit Root Tests

The empirical analysis is based on the logarithmic values of the price variables (after scaling the prices with their respective means). It is not apparent from Figure 4 whether all price series are stationary. The stationarity of the price series is tested using the augmented Dickey–Fuller (ADF) test, where the null hypothesis is that the time series is non-stationary, and the Kwiatkowski–Phillips–Schmidt–Shin (KPSS) test, where the null hypothesis is that the series is stationary (Hansen 2022).

The results of the ADF and KPSS tests are shown in Table 4, where the lag lengths in the tests were selected by minimizing Akaike's information criteria (AIC). According to both tests, the prices for charcoal, diesel, and kerosene are non-stationary, whereas the price for firewood is stationary. The ADF test indicates that the charcoal supply price is stationary, whereas the KPSS test indicates that the price is borderline non-stationary, with a p-value of 0.049. Table 4 shows that the estimated correlation coefficient from the Dickey–Fuller regression is 0.765, which is well below one. Thus, we cautiously conclude that the supply price is stationary. The first differences in the prices of charcoal, diesel, and kerosene are stationary. Thus, the prices of charcoal, diesel, and kerosene are integrated of order one ($I(1)$), whereas the prices for firewood and charcoal supply are integrated of order zero ($I(0)$).

Table 4. Augmented Dickey–Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests for the unit root of log real prices. Lag length selection is based on minimizing Akaike's Information Criteria (AIC). Sample period from June 2010 to January 2021.

		ADF				KPSS		
Variable	Symbol	Lags	$\hat{\rho} - 1$	ADF	p-Value	Lags	KPSS	p-Value
Charcoal	$\ln p^c$	4	−0.069	−2.23	0.195	6	1.04	<0.010
Diesel	$\ln p^d$	2	−0.020	−1.33	0.616	6	1.07	<0.010
Kerosene	$\ln p^k$	5	−0.015	−1.49	0.540	6	1.29	<0.010
Firewood	$\ln p^f$	0	−0.292	−4.44	0.000	5	0.19	>0.100
Supply	$\ln p^s$	0	−0.235	−4.21	0.001	5	0.47	0.049

4.4. Empirical Framework

Standard econometric tools used to analyze price transmission and market integration are based on the idea of cointegration (Engle and Granger 1987; Fackler and Goodwin 2001; McNew 1996; von Cramon-Taubadel 2017). Market integration is the degree to which demand and supply shocks that arise in one location are transmitted to other locations (Fackler and Goodwin 2001). Therefore, in a competitive charcoal market with a supply chain that tends toward equilibrium by eliminating arbitrage opportunities, we expect the price of charcoal and other prices to be cointegrated (Engle and Granger 1987; McNew 1996). Our empirical modeling framework for analyzing price transmission follows, to a large extent, the discussions by Rapsomanikis et al. (2006) and Menegaki (2019).

The general autoregressive distributed lag ARDL(r, q) model for a series p_t that is a function of r lags of its own past values and current and q lags of an explanatory variable x_t (or a vector of explanatory variables) can be written as:

$$p_t = \alpha_0 + \sum_{i=1}^{r} \alpha_i p_{t-i} + \sum_{i=0}^{q} \beta_i x_{t-i} + \varepsilon_t \tag{6}$$

where ε_t is an independent and identically distributed error term. The dependent variable here is the retail price of charcoal, which is a non-stationary variable, and the explanatory variables are a mixture of $I(0)$ and $I(1)$ variables. If the variables in Equation (6) are cointegrated, we can write the long-run relationship between them as:

$$p_t = \psi_0 + \psi_1 x_t + \psi_2 T_t + \nu_t \tag{7}$$

where we have added a deterministic time trend T to the model, and ν_t is an independent and identically distributed error term. This error term is stationary if p and x are cointegrated. The Engle–Granger test for cointegration is a test for the stationarity of the residuals from the regression model in Equation (7). However, if the explanatory variables in the long-run equation are a mixture of $I(0)$ and $I(1)$ variables, as is the case here, the preferred test is the bounds test by Pesaran et al. (2001).

When p and x are cointegrated, the ARDL model in Equation (6) can be reparameterized as an error-correction model:

$$\Delta p_t = \delta_0 - \gamma(p_{t-1} - \psi_1 x_{t-1} - \psi_2 T_t) + \sum_{i=1}^{r-1} \alpha_i \Delta p_{t-i} + \sum_{i=0}^{q-1} \beta_i \Delta x_{t-i} + \varepsilon_t \tag{8}$$

where the lag lengths r and q are sufficiently long to make the model dynamically complete. We rewrite this equation to obtain the unconstrained form of the error-correction model:

$$\Delta p_t = \delta_0 + \theta_0 p_{t-1} + \theta_1 x_{t-1} + \theta_2 T_t + \sum_{i=1}^{r-1} \alpha_i \Delta p_{t-i} + \sum_{i=0}^{q-1} \beta_i \Delta x_{t-i} + \varepsilon_t. \tag{9}$$

The ARDL bounds test is a Wald, or F-test, of the restriction $\theta_0 = \theta_1 = 0$ on the parameters in Equation (9). The null hypothesis is that there is no cointegration. The rejection of the null hypothesis suggests the presence of a cointegration relationship. Furthermore, a t-test of the hypothesis that $\theta_0 = 0$ versus the alternative that $\theta_0 < 0$ suggests cointegration. The distributions for these two tests are nonstandard, and the approximate critical values can be found in the work by Kripfganz and Schneider (2020).

The full error-correction model specification for the reduced form of the retail charcoal price function in Equation (5) to be estimated is

$$\begin{aligned} \Delta \ln p_t^c = \delta_0 - \gamma\Big(&\ln p_{t-1}^c - \psi^d \ln p_{t-1}^d - \psi^k \ln p_{t-1}^k - \psi^f \ln p_{t-1}^f - \psi^s \ln p_{t-1}^s - \psi^T T_{(t-1)}\Big) \\ &+ \sum_{j=1}^{r-1} \alpha_j^c \Delta \ln p_{t-j}^c + \sum_{j=0}^{q_d-1} \beta_j^d \Delta \ln p_{t-j}^d + \sum_{j=0}^{q_k-1} \beta_j^k \Delta \ln p_{t-j}^k \\ &+ \sum_{j=0}^{q_f-1} \beta_j^f \Delta \ln p_{t-j}^w + \sum_{j=0}^{q_s-1} \beta_j^s \Delta \ln p_{t-j}^s + \varepsilon_t. \end{aligned} \tag{10}$$

where the length of the autoregressive part is r, and the lengths of the distributed lags are denoted by q_p, q_k, q_f, and q_s for diesel, kerosene, firewood, and supply prices, respectively. This corresponds to an ARDL(r, q_d, q_k, q_f, q_s) model.

5. Results and Discussion

The estimated parameters for the error-correction model parameterization of the ARDL model are reported in Table 5. Schwartz's Bayes Information Criteria (BIC) were used to select the lag lengths in the model, resulting in an ARDL(4,0,1,0,0) model. The BIC tend to favor a more parsimonious model specification compared to the AIC, thus reducing the risk of overfitting.

Table 5. Long- and short-run estimation results for the error-correction model. Sample period: June 2010 to January 2021.

		Full Model				Reduced Model			
	Variable	Parameter	Std. Err	*t*-Value	*p*-Value	Parameter	Std. Err	*t*-Value	*p*-Value
Long-run results	$\ln p_t^d$	0.2600	0.3417	0.76	0.448				
	$\ln p_t^k$	0.5922	0.4456	1.33	0.187	0.8791	0.1694	5.19	0.000
	$\ln p_t^f$	−0.1704	0.2710	−0.63	0.531				
	$\ln p_t^s$	0.7437	0.1875	3.97	0.000	0.7105	0.1697	4.19	0.000
	trend	0.5040	0.0698	7.22	0.000	0.5176	0.0638	8.11	0.000
Short-run results	$\Delta \ln p_{t-1}^k$	−0.6696	0.3294	−2.03	0.044	−0.5615	0.3105	−1.81	0.073
	$\Delta \ln p_{t-1}^c$	−0.2224	0.0886	−2.51	0.013	−0.2110	0.0876	−2.41	0.018
	$\Delta \ln p_{t-2}^c$	0.2443	0.0891	2.74	0.007	0.2561	0.0880	2.91	0.004
	$\Delta \ln p_{t-3}^c$	0.2263	0.0848	2.67	0.009	0.2406	0.0833	2.89	0.005
	constant	−0.3484	0.5311	−0.66	0.513	−0.4287	0.5224	−0.82	0.414
EC	γ	−0.3307	0.0695	−4.76	0.000	−0.3473	0.0634	−5.48	0.000

The statistics for the ARDL bounds test are reported in Table 6. Both the F-test and the t-test are statistically significant at the 5% level, and we conclude that the price variables are cointegrated. The model specification is dynamically complete, as the Breusch–Godfrey LM-tests failed to reject the null hypothesis of no serial correlation for all lags from one to four. The Breusch–Pagan LM-test for heteroskedasticity rejected the null hypothesis of homoskedasticity. Thus, the estimated standard errors reported in Table 5 are not correct, and care should be taken when drawing inferences.

Table 6. Test statistics for the ARDL models in Table 5. Sample period: June 2010 to January 2021.

	Full Model		Reduced Model	
Test	Statistics	*p*-Value	Statistics	*p*-Value
ARDL F-test	5.370	0.007	7.834	0.001
ARDL t-test	−4.760	0.019	−5.476	0.001
Breusch–Godfrey AR(1)	1.371	0.242	2.292	0.130
AR(2)	4.063	0.131	3.881	0.144
AR(3)	4.342	0.227	4.050	0.256
AR(4)	5.556	0.235	4.534	0.339
Breusch–Pagan	27.23	0.000	26.62	0.000

The estimated error-correction parameter γ is statistically significant and negative. In the long-run part of the error-correction model, the trend is positive and statistically significant. The parameters of the price of kerosene and the charcoal supply price are both positive and significant. The estimated parameters for the prices of diesel and firewood are clearly not statistically significant.

Table 5 also includes the parameter estimates for the reduced ARDL model, where the diesel and firewood price variables are excluded. The parameter estimates are close to those for the full model specification. Only the parameter for the kerosene price changes noticeably, and now it has a much smaller standard error. The ARDL bounds test indicates that the price variables are cointegrated, and the Breusch–Godfrey LM-tests indicate that the model is dynamically complete. However, the residuals are still heteroskedastic.

The estimated error-correction coefficient is -0.33 for the full model and -0.35 for the reduced model. Thus, about a third of the deviation from the long-run equilibrium price is corrected for between months. The short-run model for both the full and the reduced specifications includes three autoregressive terms, indicating that a short-term dynamic adjustment process is taking place for the market price of charcoal.

Charcoal prices in Kampala increased by more than 55% between June and September 2011. This transition was not smooth, marked by a large increase in July (+35%), a decrease in August (-22%), and a final increase in September (+45%). This large and concentrated price volatility could influence, in particular, the dynamics of the short-run model, contribute to the heteroskedasticity of the residuals, and potentially result in unstable parameter estimates. The cumulative sum of the recursive residuals (CUSUM) test for parameter stability in the reduced model yielded a value of 1.63, as shown in Table 5, which is higher than the critical value of 1.14 at the 1% significance level. Figure 5 shows a graph of the recursive CUSUM along with a 95% confidence band.

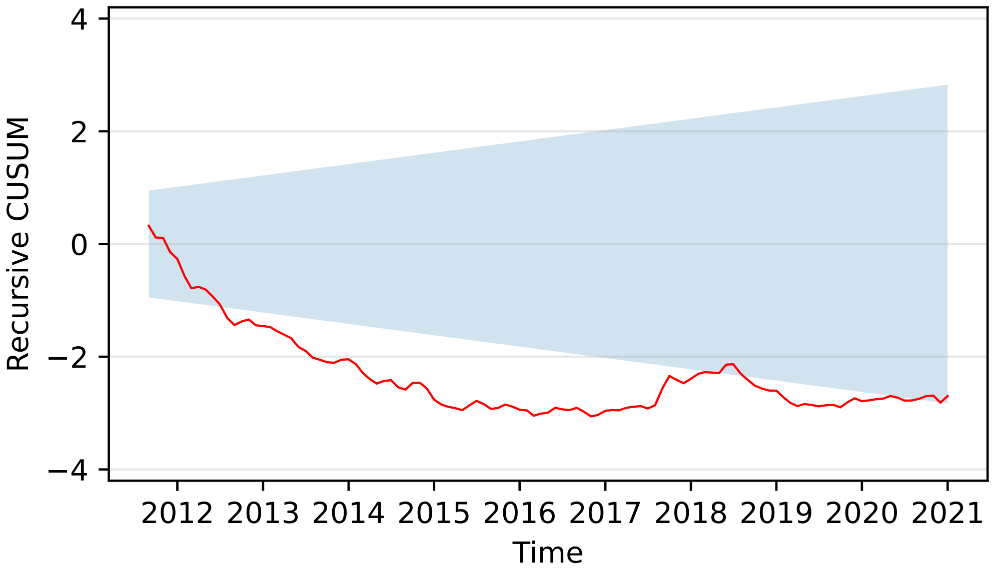

Figure 5. Recursive CUSUM plot (red line) with 95% confidence bands (shaded area) around the null hypothesis for the reduced error-correction model. Sample period: June 2010 to January 2021.

The results of the CUSUM test provide evidence of structural breaks in one or more of the price series. Using a sample period starting after the sharp increase in prices between July and September 2011, Table 7 shows the results of the ADF and KPSS tests, where the lag lengths in the tests were selected by minimizing the AIC. The results remain unchanged from those for the longer period, with charcoal, diesel, and kerosene prices as the $I(1)$ variables and firewood and charcoal supply prices as the $I(0)$ variables.

We estimated both the full and reduced error-correction models using observations from September 2011 onward and the BIC to select the lag length results for the ARDL(1,0,0,0,0) and ARDL(1,0,0) specifications, respectively, and the results are reported in Table 8. The results of the ARDL bounds tests (Table 9) are inconclusive with respect to cointegration in the full model specification. The reduced model specification exhibits cointegration between the retail and supply prices for charcoal and kerosene prices. The models are dynamically complete with homoskedastic errors. The models do not include any autoregressive terms. The three autoregressive terms included in the models in Table 5 were probably related to the three months with high price volatility in 2011.

Table 7. Augmented Dickey–Fuller (ADF) and Kwiatkowski–Phillips–Schmidt–Shin (KPSS) tests for the unit root of log real prices. Lag length selection based on minimizing Akaike's Information Criteria (AIC). Sample period: September 2011 to January 2021.

		ADF				KPSS		
Variable	**Symbol**	**Lags**	$\hat{\rho} - 1$	**ADF**	***p*-Value**	**Lags**	**KPSS**	***p*-Value**
Charcoal	$\ln p^c$	0	−0.025	−0.96	0.767	6	0.85	<0.010
Diesel	$\ln p^d$	7	−0.030	−1.92	0.321	6	0.82	<0.010
Kerosene	$\ln p^k$	1	−0.021	−2.08	0.253	6	1.08	<0.010
Firewood	$\ln p^f$	1	−0.342	−3.77	0.003	5	0.61	0.022
Supply	$\ln p^s$	0	−0.296	−4.36	0.000	5	0.21	>0.100

Table 8. Long- and short-run estimation results for the error-correction model. Sample period: September 2011 to January 2021.

		Full Model				Reduced Model			
	Variable	**Parameter**	**Std. Err**	***t*-Value**	***p*-Value**	**Parameter**	**Std. Err**	***t*-Value**	***p*-Value**
Long run results	$\ln p^d_t$	0.1623	0.2972	0.55	0.586				
	$\ln p^k_t$	0.6896	0.4177	1.65	0.102	0.8473	0.1716	4.94	0.000
	$\ln p^f_t$	−0.1756	0.2695	−0.65	0.516				
	$\ln p^s_t$	0.5020	0.1983	3.63	0.000	0.7165	0.1988	3.60	0.000
	trend	0.5020	0.0657	7.64	0.000	0.5165	0.0629	8.21	0.000
Short run results	constant	0.0506	0.3693	0.14	0.891	−0.0498	0.3458	−0.14	0.886
EC	γ	−0.2322	0.0560	−4.15	0.000	−0.2300	0.0556	−4.13	0.000

Table 9. Test statistics for the ARDL models in Table 8. Sample period: September 2011 to January 2021.

	Full Model		Reduced Model	
Test	**Statistics**	***p*-Value**	**Statistics**	***p*-Value**
ARDL F-test	3.544	0.112	5.159	0.029
ARDL t-test	−4.145	0.082	−4.135	0.036
Breusch–Godfrey AR(1)	0.017	0.897	0.027	0.870
AR(2)	0.420	0.811	0.173	0.918
Breusch–Pagan	2.30	0.130	2.53	0.112

The recursive CUSUM test for the reduced model yielded a value of 0.648, which is less than the 10% critical value of 0.850. The plot of the recursive CUSUM along with a 95% confidence band is shown in Figure 6. Thus, the parameters remained stable during this shorter sample period.

In the period after the sharp increase in nominal and real prices in 2011, our econometric analysis shows that the retail and supply prices of charcoal and the prices of kerosene are co-integrated, i.e., there exists a long-term relationship between these prices. The long-term link between prices along a supply chain from source to retail is expected, as these prices adjust to reflect changing supply and demand conditions. There are no statistically significant autoregressive or distributed lag terms in the estimated model, reflecting a lack of short-term dynamics in the retail price beyond the long-term equilibrium correction. This implies that it is not possible to test for Granger causality in this model (Enders 2014).

The trend variable has a statistically significant positive parameter value. Increasing demand from a growing urban population and reduced supply from deforestation are trends that are expected to increase the equilibrium price of charcoal, which we observed.

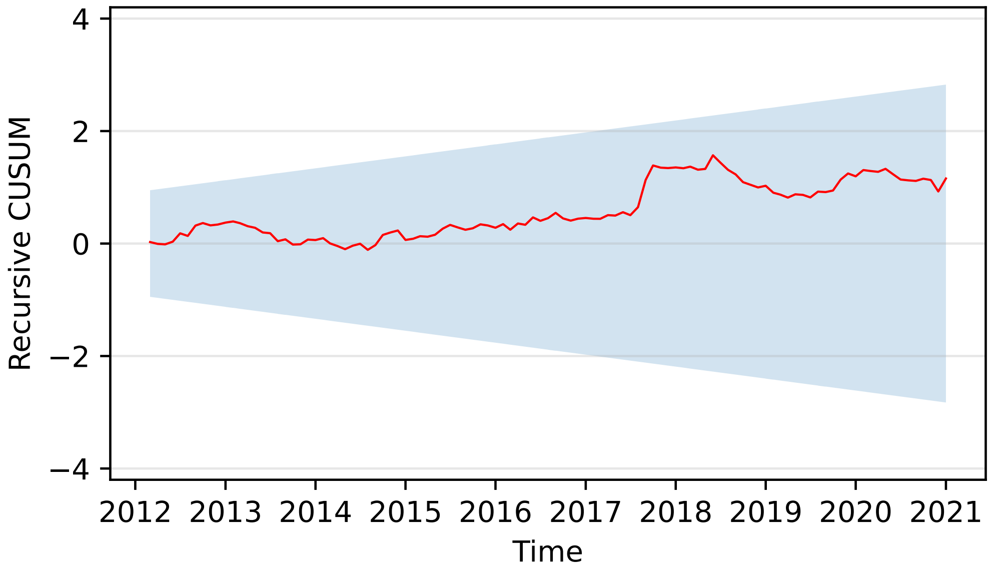

Figure 6. Recursive CUSUM plot (red line) with 95% confidence bands (shaded area) around the null hypothesis for the reduced error-correction model. Sample period: September 2011 to January 2021.

The simple correlation between the retail price of charcoal and the price of kerosene (and diesel) is negative (Table 3), which can be seen in Figure 4. However, the results of the ARDL model show a positive long-term relationship between the retail prices of charcoal and kerosene. The price of kerosene, which is an imported petrol product, reflects world market conditions. An increase in the kerosene price could see households substituting kerosene for charcoal, thus increasing the demand and the equilibrium price for charcoal. The absence of a short-term link between kerosene and charcoal prices suggests that there is limited short-term substitution between charcoal and kerosene. This result is consistent with the short-term lock-in effects related to household investments required in new cookstove equipment required to change cooking fuel types.

6. Conclusions

Charcoal is the dominant energy source in urban areas in Uganda, as is the case in many countries in sub-Saharan Africa. The Walk-to-Work protests in 2011 came at a time of high inflation and sharply increasing prices for charcoal and petroleum products. Retail prices are expected to reflect prices, costs, and market conditions along the supply chain. In functioning markets, these prices tend to be in long-term equilibrium. We used monthly price data to test for cointegration in an error-correction model. As the price data were integrated of order zero and one, the ARDL bounds test was used. We found that there was a long-term relationship between the retail price of charcoal and the supply prices of charcoal and kerosene (which is a substitute energy source for end users). Firewood and diesel prices were not statistically significant in the model. The long-term equation exhibited a positive trend, indicating that the retail price of charcoal increased more over time than implied by the supply price of charcoal and the price of kerosene. The specific reasons for this increase in retail prices were not possible to determine with the available data.

Our analysis showed that prices along the supply chain tended to be in long-term equilibrium. Therefore, policies that affect the supply and/or demand sides of charcoal will have ripple effects throughout the chain. The different possible causes of the positive time trend in our model have different policy implications. As discussed by Rose et al. (2022) and Mensah et al. (2022), the continued growth of urban populations will keep the demand for charcoal high and put further pressure on the supply chain. Improved forest management and replanting are important to maintain supply volume. However, as argued by Mensah et al. (2022), there is room for technical improvements in the small-scale production of charcoal.

Another possible reason for the upward trend in charcoal prices could be an increase in transportation costs as a result of increased transportation time, with everything else held constant. Kampala, like many other African cities, experiences severe traffic congestion, leading to long delays. The lockdown and traffic restrictions imposed during the COVID-19 pandemic may serve as a natural experiment to test the effect of traffic congestion on charcoal prices.

With only price data available, we were limited in our analysis of spatial equilibria and price patterns. Additional price data, for example, from sources similar to the CPI base data used here, with spatial information would allow for a more detailed analysis of the spatial patterns of price linkages and price change transmissions. This could also open the possibility for a more detailed analysis of transportation costs and supply-side issues. As several countries are implementing different charcoal policies, including production bans, the analysis of cross-border effects is relevant for understanding domestic price changes. Another avenue could be to explore the margins along the supply chain to better understand how competitive the different segments are and whether there may be excessive margins due to the structure of the market.

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Abbreviations

The following abbreviations are used in this manuscript:

ADF	Augmented Dickey–Fuller
AIC	Akaike's information criteria
ARDL	Autoregressive distributed lag
BIC	Schwartz's Bayesian information criteria
CPI	Consumer price index
CUSUM	Cumulative sum of recursive residuals
KPSS	Kwiatkowski–Phillips–Schmidt–Shin
UBOS	Uganda Bureau of Statistics
UGX	Ugandan Shilling

Notes

1. Also, see the recent reviews by von Cramon-Taubadel and Goodwin (2021) and Graubner et al. (2021).
2. https://worldpopulationreview.com/ (accessed on 13 June 2023).
3. https://www.globalforestwatch.org/, (accessed on 13 June 2023).

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