Trees, Forests and People 18 (2024) 100678

Contents lists available at ScienceDirect

Trees, Forests and People

journal homepage: www.sciencedirect.com/journal/trees-forests-and-people

The charcoal footprint of greater Accra on the Afram Plains: Urban energy consumption and forest degradation in Ghana

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ARTICLE INFO

Keywords:
Charcoal consumption
Urban energy demand
Deforestation
Afram Plains
Greater Accra
Ecological footprint
Sustainable resource management
Urbanization
Sub-Saharan Africa
Forest degradation

ABSTRACT

Rapid urbanisation in sub-Saharan Africa is leading to increased energy consumption and a growing reliance on charcoal as a fuel source, with significant environmental implications. This study examines the impact of charcoal consumption in Greater Accra, Ghana, on the Afram Plains ecosystem. Employing a mixed-methods approach, including geographical analysis, quantitative data collection, and sustainability assessment, we evaluate the charcoal footprint of Greater Accra. Our findings reveal that charcoal remains the dominant cooking fuel in Greater Accra despite increased access to electricity, resulting in an estimated loss of 354,479 trees annually in the Afram Plains. This demand creates an ecological deficit of 18,850 hectares/yr, significantly exceeding the ecosystem's regenerative capacity. We observe complex dynamics between urban energy needs and rural resource sustainability, highlighting socio-economic factors driving persistent charcoal use. The study proposes a conceptual framework integrating urban demand, rural supply, ecological impact, and natural regeneration. Our research contributes to urban sustainability literature, offering insights for policymakers to develop more sustainable energy strategies, including quota systems for harvesting, promoting alternative cooking fuels, community-based forest management, and improved charcoal production technologies. This case study provides valuable lessons for other rapidly urbanizing regions facing similar sustainability challenges in sub-Saharan Africa.

Introduction

Rapid urbanisation in sub-Saharan Africa presents significant challenges for sustainable resource management and climate mitigation (Awumbila, 2017). According to the United Nations, the urban population in the region is projected to increase from 472 million in 2020 to 1.07 billion in 2050, accounting for 55 % of the total population (United Nations Department of Economic and Social Affairs, 2019a). This unprecedented urban growth, rising income levels, and changing consumption patterns have increased the demand for energy and natural resources, especially in the residential sector (Li et al., 2021; Shinkhede et al., 2023; Walia et al., 2022). A critical concern is the extensive reliance of urban households on charcoal as an energy source, with profound implications for forest degradation and greenhouse gas emissions (Flammini et al., 2023; Vihi et al., 2022; Zhang et al., 2021).

Charcoal, a solid fuel derived from the carbonisation of wood or other biomass, is a significant problem in sub-Saharan Africa. It is widely used for cooking and heating in urban areas, where access to modern energy sources such as electricity and gas is limited or expensive (Branch et al., 2023; Defo et al., 2021). Approximately 80 % of African urban dwellers rely on charcoal, contributing to an annual loss of about 3.5 million hectares of forest (Erakhrumen, 2011; Ghilardi et al., 2013). The production and consumption of charcoal also emit significant amounts of carbon dioxide and black carbon, contributing to global warming and air pollution (Blanco-Donado et al., 2022; Bockarie et al., 2020; Rönkkö et al., 2023). The World Health Organization estimates that exposure to household air pollution from burning solid fuels, including charcoal, causes 3.8 million premature deaths yearly, mostly in low- and middle-income countries (WHO, 2018).

Despite its negative environmental and health impacts, charcoal is

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https://doi.org/10.1016/j.tfp.2024.100678

Available online 25 September 2024

deeply ingrained in the culture of sub-Saharan Africa. It provides important socio-economic benefits for millions of people. It is a cheap and convenient energy source for urban households, especially the poor and vulnerable, who spend a large share of their income on energy (Zulu and Richardson, 2013a). The charcoal industry also generates income and employment for rural producers, traders, and retailers, who are often marginalised and lack alternative livelihood options (Arko et al., 2024a). Additionally, charcoal is culturally embedded and preferred by many urban consumers, who value its high calorific value, long-burning time, and suitability for traditional cooking methods (Bailis et al., 2015a; Schure et al., 2013).

Charcoal consumption in Africa is significant, with about 90 % of the continent's harvested wood being used for energy production, primarily for cooking (Defries et al., 2010; IEA, 2019; Mwampamba, 2007a; Singer and Peterson, 2011; WWF, 2011). Wood fuel dominates the primary energy mix in sub-Saharan Africa, accounting for 60 % of the region's total energy use (African Development Bank and WWF, 2012; IEA, 2017). The demand for charcoal has been growing at an average rate of around 4 % since 2000 and is expected to continue playing a dominant role in the foreseeable future (International Energy Agency, 2019). Rapid population growth and urbanisation are driving increased charcoal consumption in sub-Saharan Africa (Ghilardi et al., 2013). With an expected 50 % increase in urban population by 2030 (World Bank, 2014), the demand for charcoal is projected to rise to 918 million (IEA/OECD, 2010; Njenga and Mendum, 2018).

Ghana illustrates the dominance of charcoal consumption in sub-Saharan Africa. Urban households in Ghana predominantly use charcoal as the main cooking fuel (MLNR, 2016). The country has become the fourth-largest charcoal producer globally, with the transition and savannah zones being the main charcoal production hotspots (Forestry Commission of Ghana, 2015a). Despite increased access to electricity, covering over 94 % of Ghana's urban population (World Bank, 2021), and growing income levels (Cooke et al., 2016; GSS, 2019), charcoal remains the dominant cooking fuel in Greater Accra (the country's biggest urban area (Songsore, 2009), recording a consumption rate of 45.4 %, followed by gas at 41.4 % (Ghana Statistical Service, 2013a).

The Afram Plains, located in the Eastern Region of Ghana, is an area with significant forest resources and biodiversity (Appiah, 2013a). This semi-deciduous forest ecosystem provides numerous environmental and socio-economic benefits (Appiah, 2013b; Arko et al., 2024a), serving as a major a major source of supply of charcoal and other staple foods to Ghana's capital city, Accra (Bailis et al., 2015b). However, over-consumption of charcoal from the Afram Plains is contributing to the degradation and loss of biodiversity in the area. Our recent research revealed that charcoal production leads to the loss of nearly 400,000 trees annually in the Afram Plains and the gradual disappearance of pristine tree species (Arko et al., 2024a).

This study aims to assess the contribution of urban charcoal consumption to tree cover loss in the Afram Plains and estimate the charcoal footprint of Accra on this ecosystem. This analysis provides insight into the sustainability of charcoal as an energy source and the potential consequences of its continued use on the environment and local ecosystems. This paper contributes to the growing body of literature on urban sustainability and resource management in the context of rapid urbanisation in sub-Saharan Africa. By understanding the energy dynamics and interdependencies between the city and its distant forest ecosystem, we can inform strategies for sustainable cooking energy access in African cities. It is hoped that with this analysis, policymakers and stakeholders can better understand the environmental consequences of urban energy consumption and work towards developing more sustainable energy strategies for the region.

Methodology

This study employs a mixed-methods approach to assess the charcoal footprint of Greater Accra on the Afram Plains. Our methodology combines geographical analysis, quantitative data collection, and sustainability assessment.

Study area

Afram Plains

The Afram Plains, located in the northernmost part of Ghana's Eastern Region, is a semi-island community covering approximately 5040 km^2 with a perimeter of 303 km (Government of Ghana, 2019). It lies within the forest savannah transition zone, characterised by a mix of forest and savannah vegetation (Appiah, 2013c; Codjoe and Owusu, 2011). The area experiences high temperatures with an annual rainfall between 1300 mm and 1400 mm (Appiah, 2013b) (Fig. 1).

Greater Accra

Greater Accra, situated on the southeastern coast of Ghana, is one of Africa's fastest-growing urban areas, with an estimated population of 4.6 million in 2020 (United Nations Department of Economic and Social Affairs, 2019a). It occupies an area of 3245 km^2, constituting 1.4 % of the total land area of Ghana (Ghana Statistical Service, 2013b) (Fig. 2).

Data sources

Both secondary and primary field data were employed. Secondary data on ecological footprint was obtained from a national footprint account compiled by Global Footprint Network (Global Footprint Network, 2019). Data on urbanisation trends was sourced from the 2010 Population and Housing Census (Ghana Statistical Service, 2013b). Household charcoal use data was obtained from the seventh edition of the Ghana Living Standards Survey (Ghana Statistical Service, 2017).

Data collection

Charcoal transportation data

We collected data on charcoal quantities exiting the Afram Plains from charcoal conveyance certificates issued at the mainland port at Ekyiamanfrom and estimates from tax receipts issued at water ports at Dzemeni and Akaten. Data on the actual quantities of charcoal arriving in Accra from the Ekyiamanfrom port was obtained from the records of the forestry office at Donkokrom. Data from the conveyance certificates at forestry checkpoints at Nnundu (located on the Dzemeni Accra route) and Gwata (situated on the Akaten Accra route).

Market locations and destination data

We gathered information on charcoal destinations from interviews with charcoal truck drivers at Afram Plains and field visits to 94 market locations across 13 districts in Accra

Data analysis

Urbanization trends

Barcharts and tables and conditionally formatted tables in Excel were used to observe the population trends.

Charcoal use distribution

A choropleth map created with ArcGIS was used to observe the pattern of charcoal use distribution.

Demand pattern analysis

Geographical mapping.

- Coordinates of destination towns were determined using Google Earth Pro

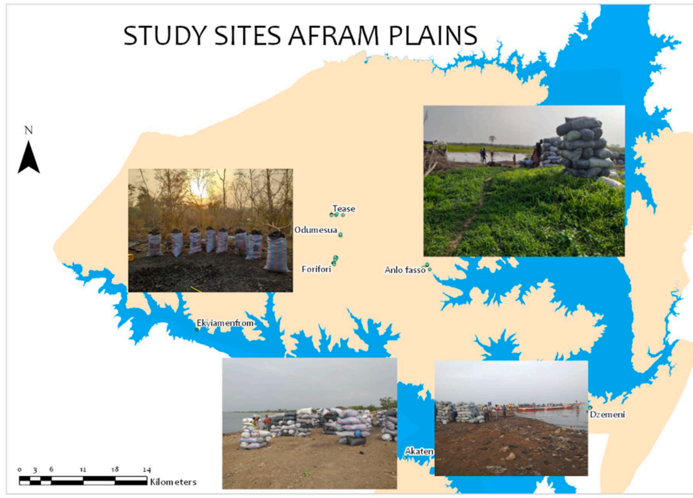

Fig. 1. Map of Afram Plains showing study locations (Arko et al., 2024a).

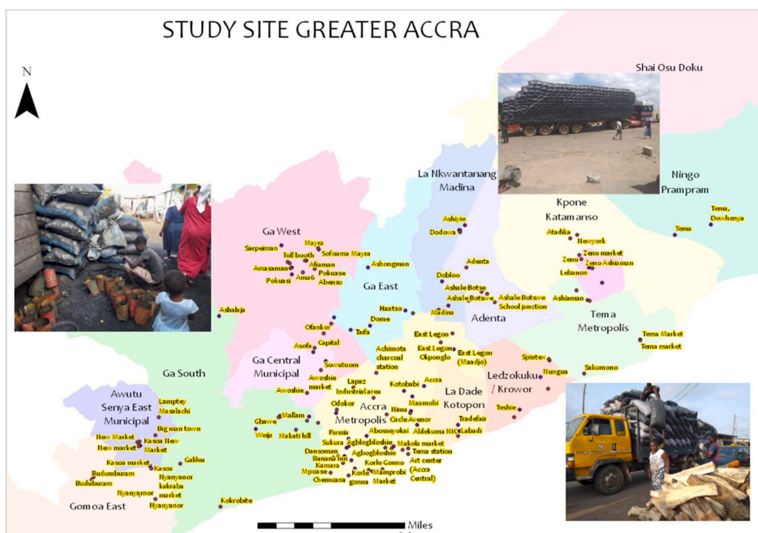

Fig. 2. Charcoal Destinations and Markets in Urban Accra.

- The Ghana shapefile was overlaid on the points to determine district locations
- Point shapefile for destination towns was produced using the Display to XY function in ArcGIS Pro

Consumption pattern visualization.

- A multiple-line table was created to link Ekyiamanfrom to various destination towns
- XY to line tool was used to generate a flow diagram
- A choropleth map was generated to visualise differences in charcoal consumption across districts

Charcoal quantity estimation

Afram plains export estimation. We estimated the quantities of charcoal exiting Afram Plains based on conveyance certificates and tax receipts.

Accra consumption estimation. We calculated the proportions of charcoal consumed in Accra from Afram Plains based on truck destination information.

Charcoal footprint calculation

Tree loss equivalent. We converted the quantity consumed to tree loss equivalents based on biophysical field survey analysis of previous study (Arko et al., 2024a).

Forest area equivalent. We calculated the forest area equivalent by dividing the number of trees lost by the forest stock density estimated in the previous study (Arko et al., 2024a).

Sustainability assessment

Annual demand calculation.

- Number of trees demanded per year = average number per bag (0.5 (Arko et al., 2024a)) × total number of bags

- Land area demanded per year = average land required per bag (15.3 m^2 (Arko et al., 2024a) × total number of bags

Comparison with regrowth rate. We compared the annually harvested extent due to the urban consumption to the estimated regrowth rate of 2800 hectares per year for the Afram Plains (based on a previous change detection analysis (Arko et al., 2024a).

Limitations of the study

- Reliance on self-reported data from charcoal truck drivers
- Potential underestimation of charcoal quantities due to informal transportation methods

Conceptual framework

The rapid urbanization in sub-Saharan Africa has significantly impacted energy consumption patterns, particularly in the residential sector. As urban populations grow, so does the demand for energy, with charcoal emerging as a dominant fuel source for cooking and heating in many African cities. This trend is particularly evident in Ghana, where, despite increased access to electricity, charcoal remains the preferred cooking fuel in urban areas like Greater Accra.

The widespread use of charcoal in urban Africa has its roots in a complex interplay of socio-economic factors, including affordability, availability, and cultural preferences. However, this reliance on charcoal has raised concerns about its environmental sustainability, echoing earlier debates about wood fuel crises in developing countries. The ecological footprint concept, on the other hand, enables us to assess the potential for this crisis. An integrated framework combining these two concepts thus helps shed light on the complex dynamics between urban energy demands and rural resource sustainability.

Greater Accra, the largest urban region in Ghana, is experiencing high demand for charcoal fuelled by a combination of factors, including rapid population growth, accelerating urbanisation, persistent energy needs for cooking and heating, economic considerations favouring charcoal as a cheap fuel source, and cultural preferences for charcoal among urban residents. As the city continues to expand and develop, these factors collectively drive an ever-increasing appetite for charcoal.

The urban demand has set in motion a supply chain that extends to distant lands like the Afram Plains. The process begins with wood harvesting from the forests, followed by the production of charcoal using crude traditional methods such as earth mound kilns. These methods, while widespread, are often inefficient and result in significant wood waste (Arko et al., 2024a). The produced charcoal is then transported to Greater Accra, where it is distributed through various urban markets to meet the cooking energy needs of the growing population.

The Ecological Footprint Concept helps quantify the environmental impact of charcoal production and consumption by considering the land area required for charcoal production (Rees and Wackernagel, 1996). This area demanded is compared to the biocapacity which represents the natural regeneration rate of the vegetation (Rees and Wackernagel, 1996; Wackernagel et al., 2018a). Biocapacity thus estimates the ecosystem's resilience and capacity to recover from human activities like charcoal harvesting.

To assess the sustainability of the urban charcoal demand on the forest ecosystem, the ecological footprint is compared to the biocapacity. This comparison allows for the identification of a potential "wood fuel gap," as posited by the Wood Fuel Crisis Theory (Eckholm, 1975; FAO, 1981). It provides insights into whether current consumption patterns can be sustained in the long term without causing irreversible damage to the Afram Plains ecosystem. If the demand exceeds the forest's ability to regenerate—an ecological overshoot is said to be occurring, indicating an impending crisis that would need urgent redressal. Intervention strategies become crucial in such scenarios.

By integrating urban demand, rural supply, ecological impact, and natural regeneration into a single conceptual framework, this model offers a comprehensive lens for understanding the sustainability challenges posed by urban charcoal consumption in most African cities, in this case, Greater Accra, on global forest sinks. These sinks are more crucial than ever before, needing preservation to continue delivering their carbon sequestration services and mitigate the dangerous impacts of climate change.

This framework not only provides a basis for analysing the current situation but also offers a structure for considering future scenarios and potential policy interventions. It underscores the interconnectedness of urban energy choices, rural resource management, and global environmental concerns, highlighting the need for holistic approaches to sustainable development.

Literature review

The concept of a "wood fuel crisis" emerged in the aftermath of the 1973 oil crisis, popularised by Eckholm (1975) and further emphasised by the UN Conference on New and Renewable Sources of Energy (FAO, 1981). This theory posited that population growth coupled with inefficient consumption would drive up demand for wood fuel, resulting in fuel shortages and widespread deforestation. The Food and Agriculture Organization (FAO) predicted an impending "wood fuel gap" where demand would outpace the regrowth of forest resources (Ribot, 2013a).

These dire predictions spurred significant action from international organisations and governments. Donor agencies like the World Bank, IMF, UNDP, and national forestry programs initiated massive tree-planting efforts to address the projected "fuelwood gaps" (Arnold and Persson, 2003; Bradley and Campbell, 1998a; Muia, 2005a). Additionally, various policy interventions were introduced to improve the efficiency of cooking stoves and charcoal kilns and to encourage consumers to switch to cleaner alternative fuels such as kerosene and liquid petroleum gas (LPG) (Mwampamba, 2007a).

However, the accuracy and relevance of the wood fuel crisis theory in today's context have been debated. The predicted widespread deforestation did not occur to the extent initially feared, suggesting that the relationship between urban wood fuel consumption and forest degradation is more complex than initially thought. Subsequent studies revealed that an increase in population growth is not always associated with the depletion of forest resources (Angelsen and Kaimowitz, 1999). Households were found to react to fuelwood shortages by switching to other types of biomass like farm residues and fossil-based energy sources or consuming less fuelwood (Dewees, 1989; Muia, 2005b).

The wood fuel crisis theory faced significant criticism for its weak assumptions and inaccurate data (Muia, 2005b; Mwampamba, 2007b). Bradley and Campbell (1998b) argued that the theory and its associated "gap theory" had been overly simplified, concluding that population growth is not directly linked to fuelwood demand and that households respond in various ways to prevent the emergence of a fuel-wood gap. Muia (2005b); Ribot (2013b) pointed out that the theory ignored several important factors, including natural revegetation, biomass harvesting outside forests, technological advancements, efficiency improvements, and the switch to alternative fuel sources. This oversight led to inaccurate predictions. Wurster et al. (2010) noted that the earlier predictions of widespread fuelwood shortages based on rising populations and shrinking forest areas did not materialize as expected. Supporting this view, Cecelski (1987) and Norman (1984) found that fuelwood use seldom posed a severe threat to deforestation, further challenging the fundamental assumptions of the wood fuel crisis theory.

Despite these criticisms, recent studies have provided evidence supporting some aspects of the wood fuel crisis theory, suggesting a more nuanced understanding is necessary. Aabeyir et al. (2016a) revealed that charcoal production degrades harvested sites. Waroux and Lambin (2012) found fuelwood extraction to be related to forest decline in Morocco's argan woodlands. Kouami et al. (2009) assessed the impact of charcoal production on woody plant species in Togo and found it depleted biodiversity, density, height, diameter of stands, and basal area of woody species. Oduori et al. (2011) found an average annual tree loss of 2.8 % due to charcoal-driven tree cutting in North Eastern Somalia. Chiteculo et al. (2018) found that charcoal production resulted in a 21–27,000 ha loss of forest cover in Angola. Muia (2005b) found a positive relationship between fuelwood use and forest stock in Kenya.

These conflicting findings highlight the complexity of the wood fuel situation and the need for context-specific assessments. In recent years, researchers have increasingly turned to the Ecological Footprint concept to better understand the environmental impact of resource consumption on ecosystems. Developed by William Rees in 1992 and further refined by Mathis Wackernagel in 1996, this metric measures the total area of productive land and water required to produce all the resources consumed and assimilate all the wastes produced by a defined population (Rees and Wackernagel, 1996). Central to this concept is the idea of biocapacity, which represents the ability of bioproductive areas to renew themselves (Galli, 2015; Shaw, 2008; Wackernagel et al., 2018b). The Ecological Footprint thus, provides a useful framework for assessing the sustainability of wood fuel consumption by comparing the demand for forest resources with the ecosystem's capacity to regenerate.

Case studies from various African cities illustrate the challenges of urban charcoal consumption. In Ghana, which has become the fourth-largest charcoal producer globally, the Afram Plains serve as a key source of charcoal for urban areas like Greater Accra (Forestry Commission of Ghana, 2015b). Recent research has revealed that charcoal production leads to the loss of nearly 400,000 trees annually in the Afram Plains (Arko et al., 2024a). In Dar es Salaam, Tanzania, Luoga et al. (2000) found that charcoal consumption has led to deforestation and forest degradation in the surrounding regions. Abbot and Lowore (1999) reported that the demand for charcoal in Nairobi, Kenya, has resulted in the unsustainable exploitation of the nearby Mau Forest, a crucial water catchment area. In Kampala, Uganda, Tabuti et al. (2003) highlighted that the high demand for charcoal has led to significant deforestation in the country's central and northern regions.

While the initial wood fuel crisis theory may have overestimated immediate threats, recent evidence suggests that unsustainable wood fuel harvesting can indeed lead to significant environmental impacts in certain areas. The application of the Ecological Footprint concept to wood fuel consumption used in this study provides a more nuanced understanding of the balance between resource demand and ecosystem regeneration.

Results

Ghana's growing ecological footprint

Ghana's ecological landscape has undergone a significant transformation over the past six decades, shifting from a state of abundance to one of deficit, as revealed by historical data from the National Footprint Accounts (Fig. 3). In 1961, the country enjoyed a period of ecological abundance, with a substantial biocapacity reserve of 1.8 hectares per person and a modest ecological footprint per capita of 1.1 hectares, while the country's biocapacity per capita stood at an impressive 2.9 hectares (Fig. 3). This surplus indicated that Ghana's ecosystems could generate more resources than its population consumed.

This ecological prosperity did not last long. A pivotal shift occurred in 1996 when Ghana's ecological footprint began to escalate, surpassing its biocapacity and marking the onset of an ecological overshoot (Fig. 3). By 2016, the situation had deteriorated further, with Ghana facing an ecological deficit of approximately 0.65 hectares per person (Fig. 3). This deficit signifies that the country now requires more resources than its ecosystems can sustainably provide, revealing an unsustainable pattern of resource consumption.

The surge in Ghana's Ecological Footprint is closely tied to the escalating demand for forest products (Fig. 4), revealing the critical impact of forest resource exploitation on the country's ecological balance.

A key driver of Ghana's fast-growing forest footprint is the increasing consumption of biomass energy, particularly charcoal. According to Ghana's National Energy Statistics, biomass energy consumption has risen steadily since 2010, reaching 2977 Ktoe in 2019 (Fig. 5) and representing 37.8 % of the total energy consumption (Energy Commission-Ghana, 2019). Within the biomass energy mix, charcoal has maintained the largest share, with consumption rising consistently since 2000 (Fig. 6).

The residential sector, particularly urban households, has been the country's largest biomass energy consumer, mainly charcoal (Dongzagla and Adams, 2022). The residential sector consumes about 86.2 % of biomass (Energy Commission-Ghana, 2019). In 2020, households consumed an estimated 86 % of total biomass, while the industrial and services sectors consumed 9.4 % and 4.4 %, respectively (Energy Commission-Ghana, 2021). This high domestic consumption is further emphasized by the fact that 91 % of roundwood in Ghana is used for charcoal production, with only 9 % used for industrial purposes (Food and Agriculture Organization, n.d.).

Rapid urbanization of greater Accra

Ghana's rapid urbanization presents a complex demographic and

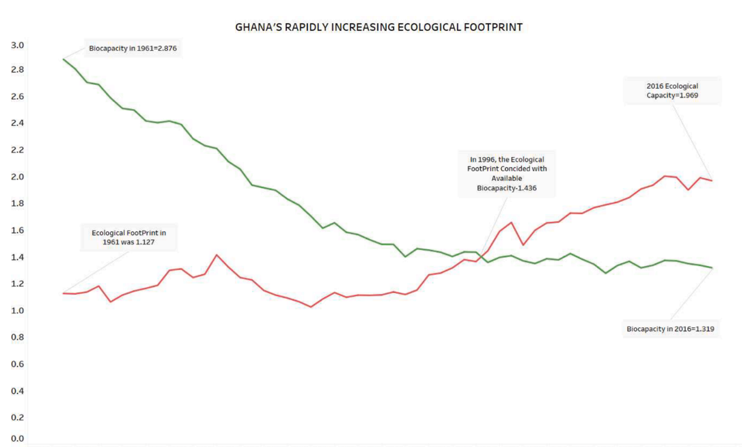

Fig. 3. Ghana's Growing Ecological Footprint. Author's construct using data from National Footprint Accounts (data sourced from (Global Footprint Network, 2019).

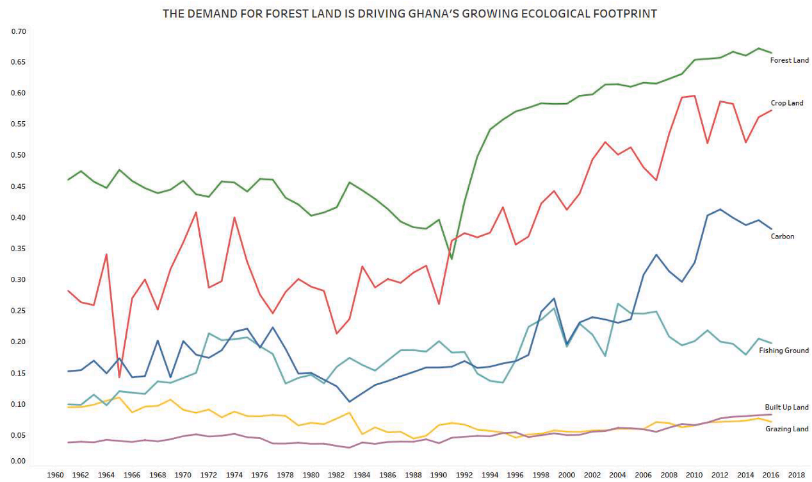

Fig. 4. Predominance of Forest Footprint in Ghana's Growing Ecological Footprint, Author's construct using data from National Footprint Accounts (data sourced from (Global Footprint Network, 2019).

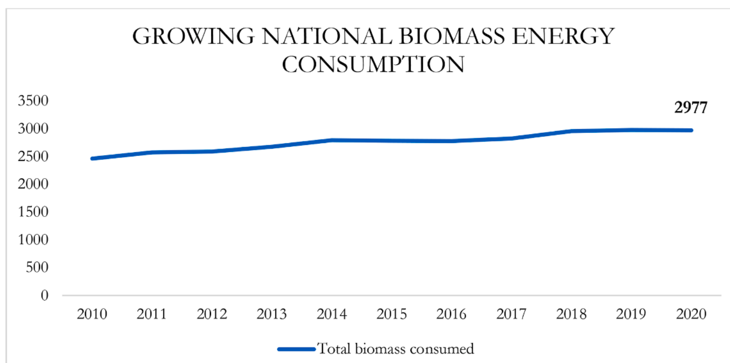

Fig. 5. National energy consumption based on National Energy Statistics (2000–2019) and the 2021 energy Outlook for Ghana, Demand and Supply Outlook.

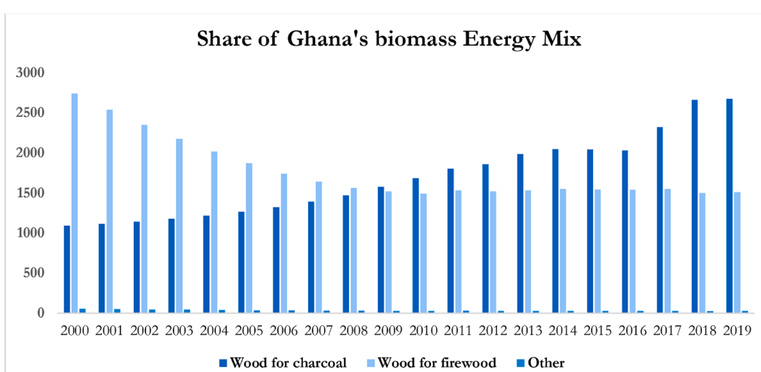

Fig. 6. National Biomass Energy Mix based on National Energy Statistics (2000–2019).

spatial transformation picture. The country's urban population has tripled between 1990 and 2017 (Fig. 7), reflecting a dramatic shift in settlement patterns (United Nations Department of Economic and Social Affairs, 2019b). This trend is further evidenced by the growth of the urban population from 8.3 million (43.8 % urban) in 2000 to 12.5 million (50.9 % urban) in 2010, with an annual growth rate of 4.2 %, significantly outpacing the national average of 2.5 % (Fig. 8) (Ghana Statistical Service, 2013b).

Urbanization has been particularly pronounced in the Central, Eastern, and Greater Accra regions. A set of 16 rapidly urbanizing cities, including Amanfrom, Madina, Buduburam, and Kasoa, have undergone remarkable transformation (Table 1). These localities, once rural communities with populations below 5000 in 1970–1984, have seen exponential growth. For instance, Amanfrom's population surged from 112 to 119,467, Odupon Kpehe (Kasoa) from 863 to 69,384, and Gbawe from 608 to 69,356 between 1970 and 2010. The emergence of new urban centres is exemplified by Mandela, which did not exist in 1984 but had a population of 61,880 by 2010 (Table 1). Suburban areas surrounding central cities like Accra have experienced substantial population growth (Yankson and Bertrand, 2012a). A striking example is Ashaiman, where the population nearly quadrupled from 50,912 in 1984 to 190,972 in 2010 (Fig. 9).

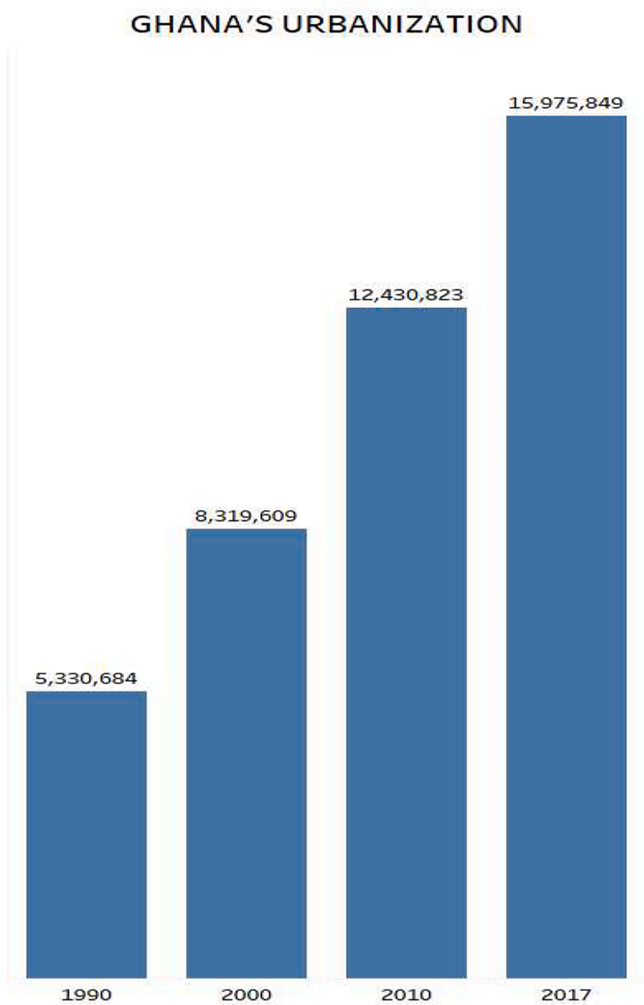

Fig. 7. Ghana's Rapid Urbanization using data from the World Bank Estimates based on (United Nations Department of Economic and Social Affairs, 2019b).

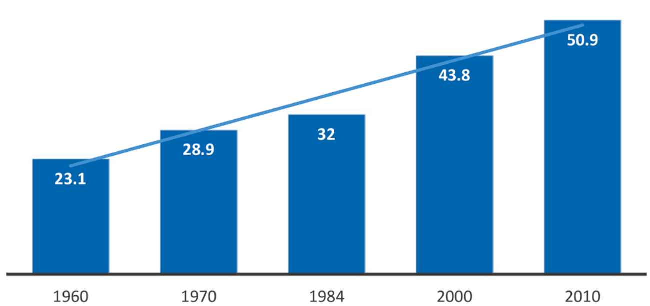

Fig. 8. Urbanization trend in Ghana using data from the 2010 Population and Housing Census (Ghana Statistical Service, 2013b).

Greater Accra stands out as the fastest-urbanizing region in Ghana (Government of Ghana, 2015) and one of the fastest-growing in West Africa (World Bank Group, 2017; Yankson and Bertrand, 2012b). Originating as a small coastal fishing village in the sixteenth century, Accra has evolved into a major metropolitan area. The Greater Accra Metropolitan Area (GAMA) saw its population increase from 4.75 million in 2000 to about 6.48 million in 2010, with projections reaching 8.8 million by 2035 (Government of Ghana, 2015). Despite occupying <1 % of the national territory, GAMA accounted for about 15 % of the national population and over an estimated quarter of the national GDP in 2010 (Government of Ghana, 2015).

The urban extent of GAMA has expanded significantly (Addae and Oppelt, 2019), stretching beyond its original boundaries to encompass parts of the Central and Eastern Regions (World Bank Group, 2017). This expansion includes the emergence of dormitory settlements like Budumburam and Kasoa to the west of Accra, addressing the growing need for affordable housing (Yankson and Bertrand, 2012a), and hence their inclusion as part of Greater Accra in this study.

Urbanization and charcoal use

The rapid urbanization of African cities, including Greater Accra, has led to significant urban sprawl beyond the original city boundaries. This expansion is largely driven by the growing demand for affordable housing and land (UN-Habitat, 2022). However, this sprawl presents substantial challenges for city authorities, who struggle to provide essential services such as water, sanitation, and electricity to these newly urbanized areas (UN-Habitat, 2020; World Bank, 2015).

Without reliable modern energy services, many households in these expanding urban areas turn to traditional fuel sources to meet their cooking energy needs (Mulenga et al., 2019). Charcoal emerges as a predominant choice for cooking fuel in these contexts. This trend is clearly illustrated in the most recent Ghana Living Standards Survey (GLSS7) data, which reveals that over 50 % of urban households in six of the urban Accra districts studied still primarily rely on charcoal for cooking (Fig. 10) (Ghana Statistical Service, 2017).

Demand pattern of charcoal from Afram plains to Accra

The flow of charcoal from the Afram Plains to various destination points in Accra, as illustrated in Fig. 11, provides a visual representation of the supply chain connecting rural production areas to urban consumption centres. This pattern of distribution underscores the strong linkage between the Afram Plains' forest resources and Greater Accra's energy demands, depicting the urban-rural resource dynamics.

Fig. 12 further details the distribution pattern of charcoal from the Afram Plains to Accra. This diagram offers insights into the complexity of the charcoal supply chain, highlighting the various routes and potential intermediary points through which charcoal travels from its source in the Afram Plains to its final destinations in Accra.

Charcoal use in greater Accra and tree cover loss of Afram Plains

The analysis of charcoal flow from the Afram Plains to Accra reveals the significant impact of urban charcoal consumption on rural forest resources. Fig. 13 illustrates the proportions of charcoal reaching Accra from three key locations in the Afram Plains: Ekyiamanfrom, Dzemeni, and Akaten. This breakdown provides a clear picture of the supply chain and the relative contributions of different areas within the Afram Plains to Accra's charcoal demand.

Using these proportions, combined with information on the total number of charcoal bags exiting the Afram Plains (Table 2), the study estimated the actual quantities of charcoal reaching Accra from the Afram Plains (Table 3).

The environmental impact of this charcoal demand is substantial. Based on estimates from previous studies (Arko et al., 2024b), producing one bag of charcoal requires, on average, half a tree and an area of 15.3m^2. Using these figures, the study calculated the number of trees and the area of land required to meet Accra's charcoal demand (Table 4).

In 2020, Accra's demand for charcoal (708,957 bags) required approximately 354,478.5 trees, equivalent to an area of 10,847,042m^2 (1084.7 ha) per year. Strikingly, this represents about 89 % of the trees cut on the Afram Plains annually, highlighting the outsized impact of Accra's charcoal consumption on this ecosystem.

To fully understand the ecological footprint of this demand, the study considered the average age of trees used for charcoal production (20

Table 1
Top rapidly urbanising towns based on the 2010 Population and Housing Census.

City/Town	1970	1984	2000	2010
Madina	7,480	28,364	76,697	79,832
Wa	13,740	36,067	66,644	71,051
Bolgatanga	18,896	32,495	49,162	65,549
Techiman	12,068	25,264	56,187	67,241
Winneba	30,778	27,105	40,017	57,015
Hohoe	14,775	20,994	35,277	73,641
Yendi	15,346	31,633	40,336	51,727
Akim Oda	20,957	24,629	38,741	51,231
Amanfrom	112	293	12,803	119,467
Berekum	14,296	22,264	39,649	56,414
Asamankese	16,905	23,077	34,855	46,061
Kasoa	863	2,597	34,719	69,384
Gbawe..	608	837	28,989	69,356
Kintampo	7,149	13,943	28,276	42,957
Mandela	0	0	8,458	61,880
Budumburam	380	40	18,713	50,560

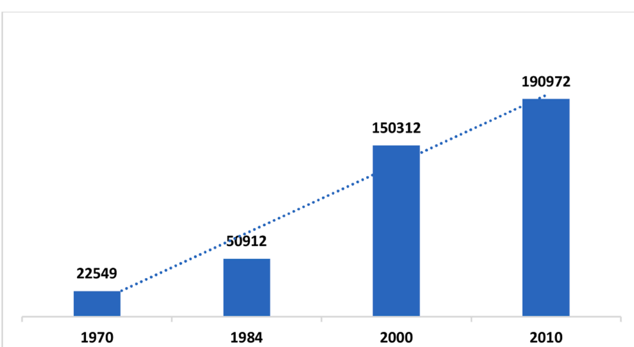

Fig. 9. Rapid Urbanization of Ashiaman using the Ghana Statistical Service, 2013b.

years). This calculation revealed that the actual area of land required for 354,478.5 trees to grow to maturity is 216,940,840m^2. When compared to the biocapacity (regenerative capacity) of the Afram Plains, estimated at 28,370,000 m^2 (Arko et al., 2024a), this results in an ecological deficit of 188,570,840m^2 (18,850 ha).

This significant ecological deficit underscores the unsustainability of current charcoal consumption patterns in Greater Accra. The demand for land to meet urban charcoal needs far exceeds the regenerative capacity of the Afram Plains, leading to ongoing degradation of the region's vegetation.

According to the wood fuel crisis theory, wood fuel demand was projected to grow at the same rate as population growth, leading to the prediction that Africa would be deforested by the end of the century to provide fuelwood for the poor (M. Arnold and Persson, 2003) (Nash and Luttrell, 2006). The "wood fuel crisis theory" suggested that Africa would be completely deforested by the end of the century due to fuelwood demand. However, this dire prediction didn't fully account for the regrowth potential of wood fuel tree species.

Trees harvested for charcoal production grow back (Fig. 14). Charcoal producers selectively harvest matured trees. The removal of the larger trees shading the young ones allows faster growth of the remaining trees by allowing increased penetration of sunlight and reducing competition. With this practice, charcoal producers can return to the same site they harvested within 5–6yrs.

Discussion

Our findings clearly illustrate the complex relationship between urban resource demands and rural resource sustainability. The rapid urbanisation of Greater Accra has led to an intensification of charcoal demand, driven by a combination of factors, including affordability, availability, and cultural preferences. This persistent demand, even in the face of modernisation and increased access to electricity, is degrading the vegetation of the Afram Plain beyond sustainable levels, aligning with aspects of the "wood fuel crisis theory".

Our results reveal a significant ecological deficit in the Afram Plains, which is directly linked to Greater Accra's charcoal consumption. This aligns with findings from other studies, such as Aabeyir et al. (2016), who demonstrated the impact of commercial charcoal production on woodland degradation in Ghana. Similarly, (Chiteculo et al., 2018) found that charcoal production resulted in a 21–27,000 ha loss of forest cover in Angola, highlighting the widespread nature of this issue across Africa.

When viewed through the lens of the Ecological Footprint Concept, we can quantify this impact: the area required to sustain current consumption levels far exceeds the ecosystem's regenerative capacity. This finding partially supports the Wood Fuel Crisis Theory's predictions of resource depletion, though not to the extent of widespread deforestation initially feared. This nuanced reality echoes the observations of (Wurster

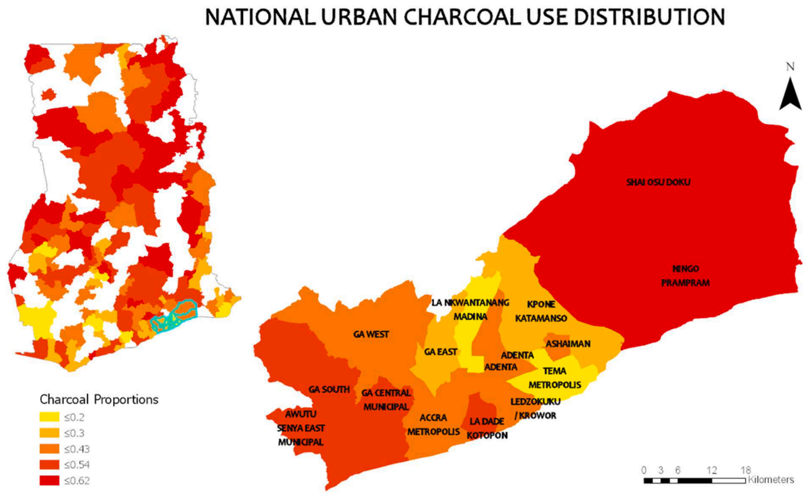

Fig. 10. Proportions of households that use charcoal as the main cooking fuel compared to gas based on the (Ghana Statistical Service, 2017).

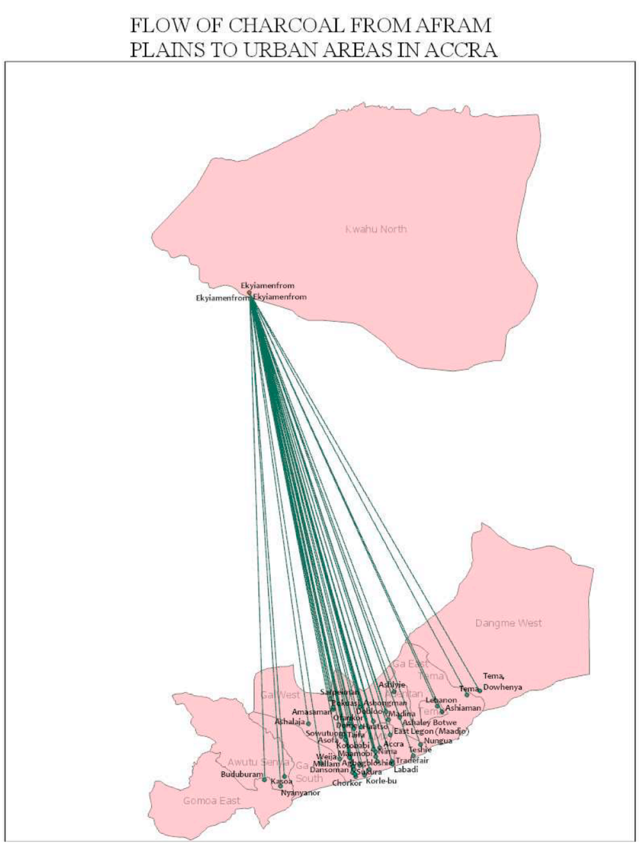

Fig. 11. Flow of Charcoal from Afram Plains to various destination points in Accra.

et al., 2010), who noted that earlier predictions of widespread fuelwood shortages did not materialise as expected.

The rural-urban dynamics highlighted in our framework are evident in the flow of charcoal from the Afram Plains to Greater Accra. This relationship raises critical questions about equitable resource distribution and sustainable development, similar to issues identified by (Zulu and Richardson, 2013b) in their study of charcoal, livelihoods, and poverty reduction in sub-Saharan Africa. While the environmental impact of charcoal production disproportionately affects rural ecosystems, the benefits of resource extraction are largely reaped in urban centers.

Interestingly, our study reveals a glimmer of hope through the observed resilience of charcoal tree species. Their capacity for natural regeneration within a relatively short timeframe of 5–6 years presents opportunities for improved forest management. This finding aligns with our framework's concept of biocapacity and resonates with the work of (Ribot, 2013b), who challenged overly simplistic notions of deforestation in West African dryland forests.

The socio-economic factors driving charcoal demand in urban areas, as outlined in our framework, are complex and deeply rooted. This persistence echoes findings by (Mwampamba, 2007b), who noted the continued dominance of charcoal in urban Tanzania despite predictions of a transition to modern fuels. Our results also align with those of (Bailis et al., 2015a), who highlighted the cultural embeddedness of charcoal use in many African urban contexts.

Our findings, when interpreted through the conceptual framework, point to several key areas for policy intervention. First, there's a clear need for optimizing harvest cycles to balance charcoal production with forest sustainability. This approach is supported by studies like (Kouami et al., 2009), who assessed the impact of charcoal production on woody plant species in Togo and emphasized the need for sustainable management practices.

Moreover, the urban-rural dynamics revealed by our study suggest that addressing energy poverty in cities like Greater Accra requires a holistic approach. This aligns with recommendations from (Schure et al., 2013), who emphasized the importance of formalizing charcoal value chains to improve livelihood outcomes in Central and West Africa.

Our conceptual framework, integrating urban demand, rural supply, ecological impact, and natural regeneration, provides a comprehensive lens for understanding the sustainability challenges posed by urban charcoal consumption in Greater Accra. While the current trajectory is unsustainable, our findings, along with those from other studies across Africa, suggest potential pathways towards a more balanced relationship between urbanization and environmental conservation. By leveraging the natural regeneration capacity of forest ecosystems, engaging local communities, and implementing targeted policies, it may be possible to meet urban energy needs while preserving crucial ecosystem services. This study thus contributes to the broader understanding of energy poverty as a complex socio-economic issue, requiring solutions that address both access to modern energy services in urban areas and sustainable resource management in rural regions.

Conclusion

This study has illuminated the complex dynamics between urbanisation, energy consumption, and forest degradation in Ghana, revealing

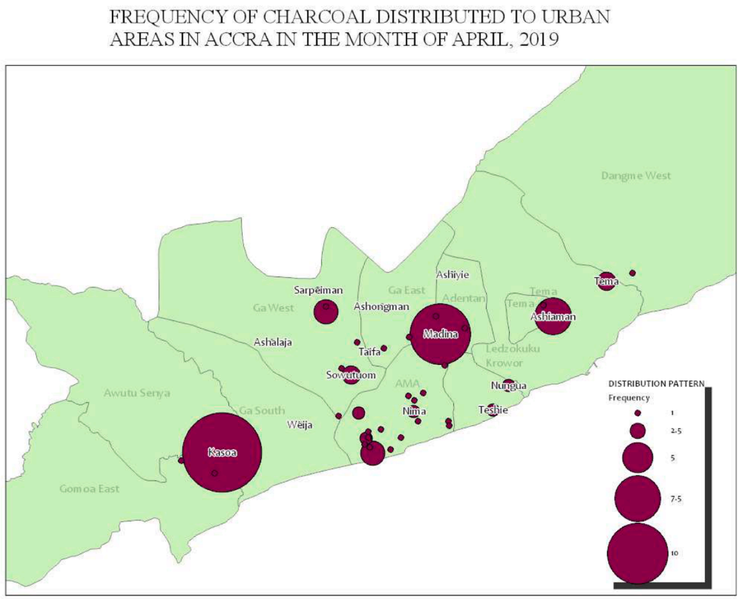

Fig. 12. Distribution pattern of charcoal from Afram Plains to Accra.

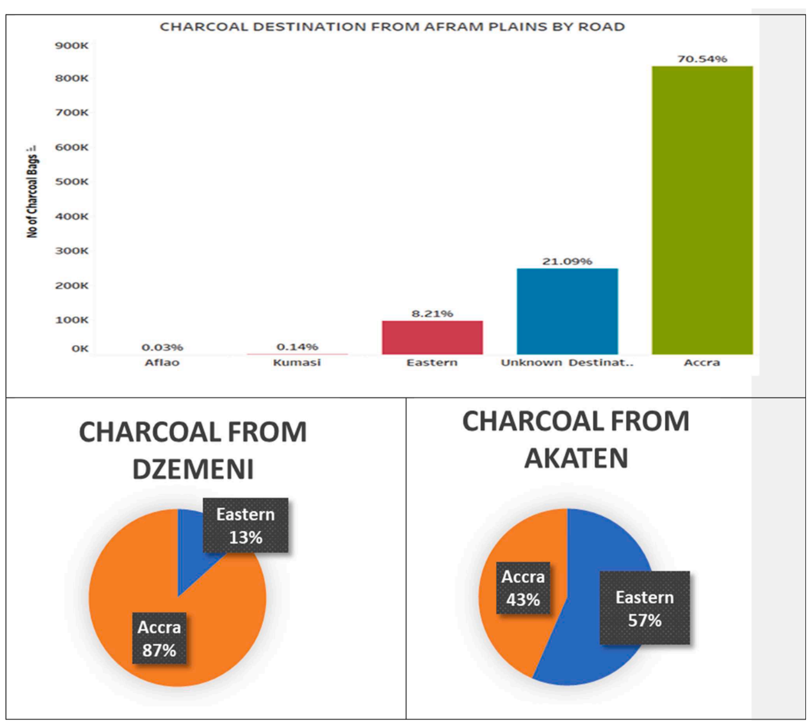

Fig. 13. The proportions of charcoal reaching Accra from Ekyiamanfrom, Dzemeni and Akaten.

a significant ecological deficit that threatens the sustainability of the country's natural resources. Our findings, including an annual loss of approximately 354,479 trees and an ecological deficit of 18,850 hectares/yr in the Afram Plains, align with aspects of the "wood fuel crisis" theory, demonstrating localised environmental pressures driven by urban energy needs.

The conceptual framework integrating urban demand, rural supply, ecological impact, and natural regeneration has proven valuable in understanding these dynamics. However, hope lies in the observed resilience of charcoal tree species and the potential for incorporating traditional ecological knowledge into management practices.

While this study provides crucial insights, limitations such as reliance on self-reported data highlight the need for further research. Future studies could focus on long-term monitoring of forest regeneration rates and exploring the socioeconomic impacts of changing energy policies on urban and rural populations.

Moving forward, policymakers should consider:

1. Implementing sustainable harvest quotas based on regeneration rates
2. Incentivizing alternative cooking fuels in urban areas
3. Supporting community-based forest management programs
4. Investing in improved charcoal production technologies

As Ghana navigates the complexities of urbanisation, a holistic

Table 2
Number of charcoal bags exiting Afram Plains (Arko et al., 2024a).

YEAR	2010	2011	2012	2013	2018	2019	2020	Total
BY LAND	412920	465050	455050	400350	278266	354200	276317	2642153
BY WATER DZEMENI	520000	520000	520000	520000	520000	520000	520000	3640000
BY WATER (AKATEN)	140400	140400	140400	140400	140400	140400	140400	982800
TOTAL	932920	985050	975050	920350	798266	874200	796317	6282153

Table 3
Computed Quantities of Charcoal Reaching Accra from Afram Plains Using the Calculated Proportion Fig. 13.

YEAR	2010	2011	2012	2013	2018	2019	2020
BY LAND	293173	330186	323086	284249	197569	251482	196185
DZEMENI	452400	452400	452400	452400	452400	452400	452400
AKATEN	60372	60372	60372	60372	60372	60372	60372
TOTAL	805945	842958	835858	797021	710341	764254	708957

Table 4
Tree cover loss and footprint of urban charcoal demand from Afram Plains.

Year	Totals bags of charcoal	Number of trees demanded	Area of land demanded/m2
2010	932920	466460	14273676
2011	985050	492525	15071265
2012	975050	487525	14918265
2013	920350	460175	14081355
2018	798266	399133	12213470
2019	874200	437100	13375260
2020	796317	398159	12183650

approach considering environmental, social, and economic dimensions is vital. Ghana can strive towards a more sustainable and equitable future by integrating sustainable practices, promoting conservation initiatives, and collaborating with local communities. This case study contributes to the broader global dialogue on sustainable urbanisation and resource management, offering valuable lessons for other rapidly urbanising regions facing similar challenges.

Declaration of generative AI and AI-assisted technologies in the writing process

While preparing this work, the author(s) used ChatGpt and Microsoft Bing to brainstorm. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the publication's content.

Fig. 14. Regrowth of between 2 and 6 months of charcoal tree species.

CRediT authorship contribution statement

Thelma Arko: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Dr Adelina Mensah:** Supervision. **Pedi Obani:** Supervision. **James Adomako:** Supervision. **Fatima Denton:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Thelma Arko reports financial support was provided by Robert-Bosch Foundation GmbH. If there are other authors, they 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

Data will be made available on request.

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