How land tenure and labor relations mediate charcoal's environmental footprint in Zambia: implications for sustainable energy transitions

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Abstract

Charcoal is the main cooking fuel in urban areas of sub-Saharan Africa and demand is expected to rise with urbanization. We explore the environmental footprint and socioeconomic drivers of charcoal production, using data from original field vegetation and producer surveys in a hotspot charcoal production area outside Lusaka, Zambia. We find that land tenure and labor market conditions structure the environmental footprint of charcoal production. Agricultural expansion is the main driver of forest conversion on customary and private (leasehold) lands where charcoal is a one-off byproduct of land-use change by farmers. By contrast, charcoal production drives forest degradation on State land, especially in Forest Reserves where agriculture is prohibited but the more intact forest is intensively harvested, largely by urban residents or, during the dry season, by nearby farmers lacking remunerative employment. Charcoal producers are remarkably varied, with sharp variation in net financial gains that are positively and significantly associated with volume produced. Strategies for improving the sustainability of charcoal production differ by land tenure type but require a combination of enhanced enforcement of existing land use restrictions, improved labor market conditions, greater support for sustainable agricultural intensification, devolution of forest management to more local level, and adoption of alternative cooking fuel sources by urban residents.

Keywords: Charcoal production, miombo woodlands, wood energy, land tenure, forest degradation

Highlights

- Land tenure and labor market conditions structure charcoal production's environmental footprint in Zambia.
- Charcoal is a one-off byproduct of agricultural conversion on customary and private lands, so is not a sustainable energy source.
- Charcoal drives forest degradation in Forest Reserves (State Lands), with low regeneration potential.
- Charcoal production creates a biomass loss of at least 50% from extraction of most tree species of all sizes (≥ 10cm in diameter).
- Rural and urban charcoal producers' effort responds to unemployment or underemployment, especially during the season when agricultural labor demand wanes.

INTRODUCTION

Energy access is a key engine of development, a priority reflected in sustainable development goal (SDG) number 7 that seeks to "ensure access to affordable, reliable, sustainable and modern energy for all" by 2030. Meeting this goal would require major energy transitions in Africa, where solid fuels (mainly fuelwood and charcoal) constituted 45.3% of the total primary energy supply in 2018 continentwide (IEA, 2020), making up an even larger share in most sub-Saharan African countries. While fuelwood consumption is declining, the demand for charcoal is consistently on the rise, with important concerns for environmental sustainability. Executing a sustainable energy transition requires a firm understanding of what currently drives the charcoal value chain and how both environmental and socioeconomic outcomes might be affected by reduced charcoal dependence in the future. Policy discussions around the greening of the charcoal value chain (FAO, 2017) require additional empirical work to understand the levers of change for, and the prospective impacts of, such an energy transition.

This study aims to inform this 'greening' of charcoal value chains by focusing on the supply side, using a case study from Zambia. We focus on understanding how land tenure and labor market conditions influence charcoal's environmental footprint, including the role of charcoal as a driver of both forest loss and rural economic activity. Our field data collection consists of a social-ecological appraisal, through forest inventory and spatial characterization of production sites, as well as a survey of charcoal producers. More precisely, we address the following specific questions: 1) What are the site conditions before and after charcoal production in terms of forest biomass density and tree species diversity? 2) Do these conditions differ between land tenure types? 3) What are the main characteristics of charcoal producers working at these sites?

We show that land tenure type structures the quality of the forest resources, the drivers and environmental outcomes of charcoal production. Land tenure types also relate to the diverse set of producers involved and the strategies they use to generate income, either selling directly to urban consumers or to wholesale buyers at the production site. Some producers are farmers, producing charcoal as a one-off byproduct of farm land expansion or as supplemental income during the dry season on nearby customary or State lands. Other producers come from outside the immediate area, traveling from more urban locations to produce charcoal on lands that are not theirs – typically on state-held property or customary lands — as their main or a complementary income source when they face un- or under-employment. We then explore the policy implications of these findings and the sustainability of charcoal production in Zambia. To the best of our knowledge, this is the first study to evaluate both charcoal's environmental footprint and producers' characteristics within the policy context of 'greening' the charcoal value chain. This study thereby offers a more holistic view of the charcoal production landscape. Such nuanced understanding is essential to inform discussions around sustainability energy transitions in sub-Saharan Africa and elsewhere.

Charcoal use is expanding in sub-Saharan Africa (SSA), especially among the 80-90% of urban or peri-urban households that use it as cooking fuel (Chidumayo and Gumbo, 2013; Mulenga et al., 2019; Shively et al., 2010; Zulu, 2010). As access to electricity increases, many observers expect charcoal demand to decrease. This has not (yet) been observed. Instead of switching to electricity as it becomes available (what is known as the "energy ladder theory"), households instead use different types of energy for different needs, a practice known as "energy stacking" (Doggart et al., 2020b; Mulenga et al., 2019). Electricity is used for lights, appliances and other electric devices. Charcoal remains the energy of choice for cooking because it is inexpensive relative to electricity or of other fuel alternatives and due to cultural preferences for the taste of food cooked over charcoal. In addition to charcoal being more affordable for cooking than electricity or other fuels–e.g., kerosene, liquid petroleum gas (LPG)(Bentson et al., 2013)– its supply is usually more reliable than existing alternatives (Maes and Verbist, 2012). It also burns cleaner than fuelwood, with less smoke and particulates (Bailis et al., 2005; Castillo-Santiago et al., 2013; Ezzati et al., 2004), and is easier to transport and store than fuelwood. Doggart et al. (2020b) shows that despite fuel switching policy in Tanzania, urban households prefer charcoal because it remains the cheapest energy source. Electricity access may reduce charcoal consumption (Mulenga et al., 2019) but this depends heavily on the relative price of electricity compared to charcoal. Charcoal demand also rises with household income (D'Agostino et al., 2015). Continued urbanization is expected to fuel rising demand for charcoal in SSA (Arnold et al., 2006; Mwampamba et al., 2013; Silva et al., 2019; Sola et al., 2017) because so far, there are no easy, widely adoptable, affordable and safe energy alternatives. So until alternative energy sources become appreciably cheaper relative to charcoal, the total charcoal demand seems unlikely to fall in the coming several years and indeed may rise further as incomes and urbanization grow (Doggart et al., 2020b).

Growing charcoal demand raises important concerns about forest and woodland ecosystems from which the biomass is extracted and for the long-term sustainability of this fuel for users. Charcoal appears an important driver of deforestation around cities and/or of forest degradation in general (Ahrends et al., 2010; Fisher, 2010; Mwampamba, 2007; Naughton-Treves et al., 2007; Sedano et al., 2020; Zulu, 2010). Wood energy (charcoal and woodfuel) is responsible to 2-7% of global greenhouse gas (GHG) emissions (Bailis et al., 2015; FAO, 2017). This reliance on charcoal can hamper countries' efforts to reduce emissions from deforestation and forest degradation, or to the sustainable management of forests to mitigate and adapt to climate change (Fisher et al., 2011).

Charcoal production and trade are ultimately heavily influenced by economic considerations. Although fiscal revenue earnings are modest due to the informal nature of the industry (SEI, 2002; Zulu, 2010), charcoal production is comparable to or higher than other major commodities produced in the region, with an annual value of US$66, 77, 81, 350 and 450 million in Ghana, Rwanda, Malawi, Tanzania and Kenya, respectively (World Bank 2009, Openshaw 2010, Minten et al. 2013, Mwampamba et al. 2013, Agyei et al. 2018).

Charcoal production relies on two fundamental inputs: forested land from which woody biomass is harvested and labor to harvest the wood, manufacture the charcoal, and transport it to urban sales outlets. Charcoal thereby supports a large and diverse network of rural and urban actors along the value chain, providing income to land owners, and to those employed or self-employed in the production and trade of charcoal. An estimated seven million people in SSA depend on the charcoal value chain as a source of income and employment, and that number could reach 12 million people by 2030 (Mwampamba et al., 2013). For example, the charcoal sector employs perhaps 300,000 people in and around Kinshasa (Democratic Republic of Congo, DRC) alone, with some of them relying on charcoal for up to 75% of their household income (Schure et al., 2014). Charcoal production thus necessarily reflects broader conditions that affect economywide labor and land allocation, including land tenure regimes and general labor market conditions.

Charcoal is generally produced with the ‘earth kiln technology’, a method that involves tree felling, log cutting and stacking, covering the log pile with a thick layer of soil, and slow wood carbonization (pyrolysis) under low oxygen conditions. Then, charcoal is recovered after breaking the kiln, which can take a few weeks. The method generally has low conversion efficiency (10-27%) (Chidumayo, 2013; FAO, 2017).

Because charcoal production with earth kiln technology entails hard physical work, the job has been described as a 'safety net' or an outlet for the rural poor 'without alternative economic opportunities' (Arnold et al., 2006). However, this is an incomplete view, as a diverse set of actors is involved in the production. Studies show that charcoal production engages many people not amongst the poorest in Uganda (Khundi et al., 2011), Zambia (Mulenga et al., 2017), Ghana (Agyei et al., 2018) and Mozambique (Smith et al., 2019), and is rather used as part of a diversified livelihood strategy to manage risk or raise funds to invest in other activities (Jones et al., 2016; Kalaba et al., 2013; Smith et al., 2017). In DRC, charcoal was shown to help reduce poverty, by supporting basic needs and investments in other livelihood activities (Schure et al., 2014), while in Ghana and Mozambique income generated by most producers was found not enough to lift producers out of poverty (Agyei et al., 2018; Vollmer et al., 2017).

Given the varied actors involved in charcoal production and trade, the sector's environmental footprint arises not only from policies that directly regulate charcoal production and trade, but also from broader policies, institutions and other influences on land and labor market conditions that influence behaviors. Functioning charcoal licensing and regulation systems can limit the benefits of charcoal production and trade for small-scale rural producers because licensing costs and bureaucratic process prove differentially prohibitive for smaller, poorer, less well-connected individuals as compared to larger commercial producers and wholesalers (Schure et al., 2013; Jones et al., 2016; Agyei et al., 2018; Smith et al., 2019). Such policies mainly serve to increase state revenues from the sector and (sometimes) to improve state control over forest extraction, but it does not necessarily provide solutions for rural poverty in production areas.

Land policies heavily influence charcoal production by defining who controls land use decisions, who stands to benefit from those decisions, and what, if any, restrictions exist on uses. Rural land policy – beyond that focused expressly on charcoal – is especially important because of the linkages between agricultural conversion and charcoal production, and because of the forests' regeneration potential.

Labor market conditions and associated policies likewise matter since charcoal production and trade require time. Factors that increase unemployment and underemployment, or that reduce wage rates among the employed, will tend to make time spent in charcoal production and trade more attractive, putting greater pressure on forest resources. The complex of land and labor relations within rural areas where charcoal is produced and along the rural-to-urban corridors through which the charcoal trade flows thereby mediate both the environmental impacts of the growing charcoal sector in SSA.

STATUS QUO OF CHARCOAL PRODUCTION IN ZAMBIA

Zambia's landscape is dominated by miombo woodlands (ca. 50 million ha) and experiences high deforestation and degradation rates (Hansen et al., 2013; ILUA II, 2016). The miombo woodlands, located in the mesic part of the savanna biome, is the most extensive seasonally dry tropical woodland in the East and Central-South Africa region, covering about 2.7 million km^2, and with a key role for the global carbon cycle, the conservation of biodiversity and the livelihoods of millions of inhabitants in the region (Frost 1996, Dewees et al. 2010). Dominated by the genera *Brachystegia*, *Julbernardia* and/or *Isoberlinia* (Fabaceae, subfamily

Caesalpinioiceae), mature undisturbed miombo is a closed deciduous non-spinescent woodland over most of its range (Campbell 1996, Chidumayo and Gumbo 2010) and fulfills most definitions of 'tropical dry forest'. Fires are a characteristic disturbance of the miombo woodlands (Barbosa et al., 1999; Ryan and Williams, 2011; Scholes et al., 1996) and nearly all fires are ignited by humans, intentionally or not, since at least the Iron Age (Chidumayo, 1997). Other vegetation types include mopane woodlands, dry evergreen forest, dry deciduous, undifferentiated woodlands among other, and more localized formation such as *Chipya* vegetation, which is a wooded grassland found in Northern Zambia, which burns fiercely (Smith and Fisher, 2001).

Zambia's energy portfolio depends heavily on biomass energy supply (~80%). Hydropower provides 80.8% of the electricity generation (GOZ, 2019), but only provided 8.6% of the national energy supply in 2016, followed by primary and secondary oil (9.5%) and coal (1.7%) (IEA, 2020). Energy policy has focused primarily on these latter supply sources. With climate change and associated impacts on rainfall patterns, however, power generation from hydropower "has been compromised" (GOZ, 2019). The 2019 National Energy Policy indicates that the high reliance on wood energy (charcoal and firewood) is due "to low access and also unreliable electricity supply, high cost of efficient alternatives, inadequate enforcement of legislation and coordination among key sector institutions." One of its objectives is promoting sustainable exploitation of biomass, but the policy does not lay out how to achieve this nor identify actions towards realizing this goal.[1]

Charcoal production was identified as the second most important driver of deforestation in Zambia, after agricultural expansion (Vinya et al., 2011). Zambia took part in the United

[1] The word 'forest' (or woodland) is only mentioned twice, in 'forestry waste' and 'efficient forest management' in the 48-page document.

Nations Collaborative Programme on REDD+ (UN-REDD), which led to the elaboration of a REDD+ national strategy, coherent with the country's economic development (Matakala et al., 2015). One objective of the REDD+ national strategy is to regulate wood fuel production, especially charcoal production. Zambia's Intended Nationally Determined Contribution (INDC) to the Paris Agreement also emphasizes national mitigation around sustainable forest management, including sustainable charcoal production.

According to the Zambian Constitution of 2016 and the Land Act 1995, all lands are vested in the President, on behalf of the Zambian people (GOZ, 2016, 1995). They recognize two land tenure types: 1) State land, which is administered by government officials in accordance with written laws, formally termed statutory tenure, and 2) customary land, which is administered by traditional authorities (Chiefs and village headmen/headwomen) based on localized customary laws, which are often unwritten.

State lands include Zambia's protected areas network, including 480 Forest Reserves comprising 175 National Forests and 305 Local Forests with an estimated combined total area of 74,361 km^2, 20 National Parks covering 63,630 km^2, and 36 Game Management Areas (GMAs) covering about 167,557 km^2 (GRZ, 2015). These protected areas are expected to host higher carbon stocks and tree species richness due to their protection status and more limited access.

Under customary tenure, which represents about 51-54% of the country's surface area, the traditional authority allocates land and gives the authorization to clear forest for agricultural purposes for smallholder farming (Sitko and Chamberlin, 2016), and provides permission for charcoal production, brick making, and timber collection (USAID, 2019). Because forest productivity levels off relatively quickly in the miombo woodlands and trees respond well to intermediate level of disturbances, some managed and/or inhabited areas in the customary lands may have equivalent or higher carbon stocks than protected areas (Chidumayo and Bakker, 2004; Jew et al., 2016; Pelletier et al., 2017).

The Forest Act of 2015 regulates access to and use of forest resources on State land and customary land for charcoal production (GOZ, 2015). The Forest Act of 2015 also vests all trees and forest produce in the President, including charcoal. Article 87 of the Act specifies that someone who “manufactures wood into charcoal or offers for sale, sells or removes charcoal in or from any State land or customary area commits an offence”, which could be considered a civil or criminal offense, if they do not have a license or permit. Any charcoal production beyond subsistence requires a permit. Permits or licenses for charcoal production and conveyance are issued by the Forest Department of the Ministry of Lands, the government agency in charge of administering and monitoring of forest resources, including protecting Forest Reserves. On customary lands, their responsibilities overlap with traditional authorities for permitting activities that impact forests. Overall, the enforcement of charcoal production licenses is minimal, however. It is estimated that as little as 5% of the charcoal is produced with a valid license (Chidumayo, 2019; Kalinda et al., 2008).

Under the Forest Act, forest clearing for agriculture is generally allowed and does not require a permit on Customary Land, nor on State land as long as it falls outside Forest Reserves, GMAs or National Parks, where agriculture is prohibited. Clearing forest is a key mechanism for an individual to claim usufruct rights to the land on State lands (outside protected areas) and on customary lands, but on the latter, approval by the village headman is required.

The Land Act of 1995 allows for customary tenure to be converted into a 99-year private leasehold, commonly referred to as private lands, which covers about 10% of the land area (Mulolwa, 2016). Once converted, customary land rights are exhausted and the land is classified as State land under private leasehold and cannot be converted back to customary tenure. Land under private leasehold title is perceived as a way to promote development through incentivizing private investment, which is made more attractive due to greater tenure security, and made feasible, as the leasehold rights are transferable and can therefore be used as collateral for a loan (Mushinge and Mulenga, 2016; USAID, 2019). However, applying for a private leasehold title is expensive and cumbersome, thus inaccessible to many smallholder farmers (Sitko et al., 2014). Other types of private leasehold are also available (USAID, 2019).

The Zambian government has also been promoting special zones, called "Farm blocks" for attracting large-scale foreign commercial agricultural investment that contemplate an area of about one million hectares of customary lands open for agricultural development (Sitko and Jayne, 2014).

From this context, we set out to examine the charcoal environmental footprint and its relationship to producers and land relations. We explore those relationships directly through primary data collection.

METHODS

Study area

This research takes place in the Mumbwa District, in Central Province of Zambia, a hot spot for charcoal production, located at approximately 200 km – about 3-4 hour drive – from the capital city, Lusaka. Our case study area covers approximately 425,000 ha, with the sample sites distributed across the study area, representing different land tenure and protection status, including State, customary and private land (Figure 1). The location for this case study was decided based on the recommendation of the Zambia Forestry Department. The fieldwork was organized and deployed from Mumbwa Town.

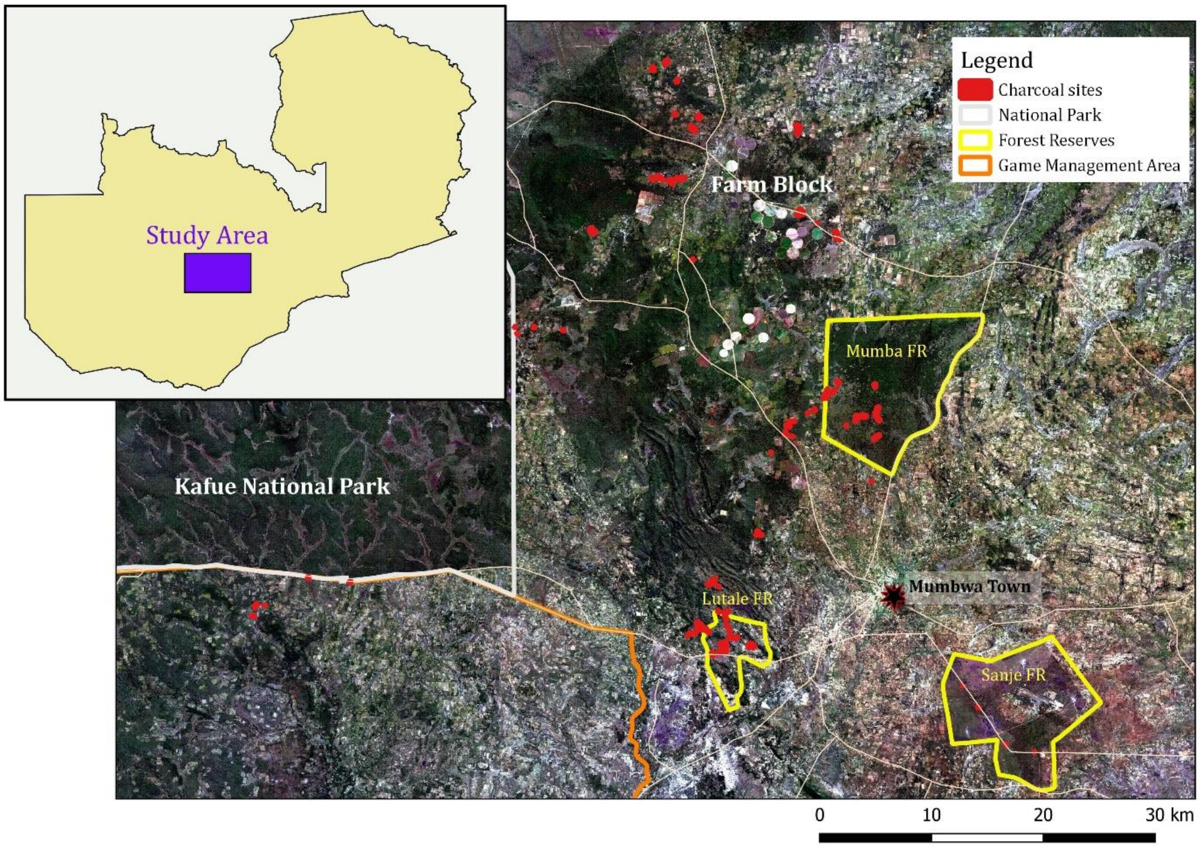

Figure 1. Map of the case study area and distribution of the field sites. The background is a Sentinel 2 true color composite (bands 4, 3, 2) for May 2019. Field data was collected from Mumbwa GMA, Lutale and Sanje local Forest Reserve, as well as in Mumba National Forest Reserve.

We contacted the representative of the Community Resource Board (CRB) for some of the targeted areas to identify charcoal production sites on State land, including in GMAs and Forest Reserves. We also followed the customary process, by meeting with village headmen/headwomen in charcoal production areas to explain the study and ask for permission to make field measurements in their area. After discussions, all authorities gave their support and provided orientation on where to find charcoal sites. At the sites, we asked all people present if we could measure the charcoal production sites using standard forestry methods and/or if they were willing to participate in a short survey of charcoal producers, after informing them about the study objectives and receiving oral consent.[2]

We deployed the field campaign in three 10-day periods to capture the seasonality of charcoal-making activities: July/August 2018, November 2018 and April 2019. For the first phase, we collected qualitative information from the charcoal producers available at the sites and used this information to build a short survey that was implemented during the second and third phases to collect data on their involvement in charcoal production and their livelihoods in general. In the next sections, we describe the field survey methods, including vegetation inventory, spatial data collection, and interviews with charcoal producers. Then, we explain the statistical data analysis.

Field vegetation survey

The purpose of the field vegetation survey was to assess the relationship between charcoal production and dry forest ecosystem, especially carbon stocks and tree species diversity at active production sites. The field team included two technicians with professional forestry degrees and two members of the surrounding communities. The latter received training and helped orient and obtain work authorization for the field team. A forestry technician with longstanding experience in vegetation survey methods and extensive local botanical knowledge led the team.

[2] Village headmen/headwomen and study participants were each provided with a written description of the research project as well as contact information.

For measuring the impact on the vegetation from charcoal production, we established the the center point of the 20-meter radius sampling plot, near the active kiln, at the center of the area of impact, for a plot size of 0.125 ha. Within each sampling plot we measured the diameter at breast height (dbh) of trees left on site (≥10cm dbh), the height and the top diameter of stumps as well as the length and the two diameters of coarse woody debris (≥10 cm diameter) found on the plot. Each individual was identified at the species-level with scientific name based on the classification of Storrs et al. (1995). Coarse woody debris was systematically measured in the North-East quadrant of the plot, for sub-plot area of 314.2 m^2. We collected other site information, including the GPS location, the vegetation type, evidence of previous impacts (presence of old stumps), fire damage, distance from the center to the farthest stump, among other characteristics. We identified whether the site was utilized for charcoal production only or if it was being converted to agriculture, that is the purpose or driver of forest clearing. We focused our work on active kilns because it was feasible to ask permission and to confirm information about the site. Older kilns can only remain visible when charcoal residues and surrounding stumps are left at the kiln site, which might not be the case after charcoal production ends, especially if the site converts to agriculture. We inventoried a total of 139 active charcoal production sites.

Spatial information on production sites and control areas

We collected spatial information on charcoal production sites. Using a handheld GPS unit (Garmin GPSMAP 64sx), we collected the waypoint at the plot center of each of the 139 vegetation inventory sites. We also used the GPS tracking feature to delimit the total area of impact for active charcoal production sites by walking the perimeter while collecting waypoints every 30 seconds. We loaded the tract spatial data into a GIS and digitized the limit of each surveyed charcoal sites to estimate the area and spatial distribution of charcoal production sites as shown in Figure 1.

Charcoal producer survey

The purpose of this survey was to understand better the role of charcoal production in the livelihood strategies of producers, including who produces, why they produce, the costs and revenues generated from their production, the strategy used to sell their charcoal, and their incentive to participate in the charcoal sector. We selected participants based on their involvement in charcoal-making as manifest in active charcoal production within our study area. One field team member was trained to obtain informed consent from the producer and then to conduct the survey with producers on-site. To facilitate participation in the survey, given the informal, and sometimes illegal nature of charcoal production, we collected no personal identification information from the producer survey respondents. Some producers surveyed did not have their own charcoal production site measured with the vegetation survey but were disposed to participate in the survey.[3] The survey was delivered in a local language spoken by the producer. A total of 55 producers were surveyed.

Biomass and tree diversity impacts

We compiled the field data collected from the three phases of the field campaign and calculated the individual biomass of each tree, stump, and coarse wood debris and took the sum of biomasses for each sample plot, that we converted into biomass density, in megagrams (Mg) per

[3] For example, in one case, the team was measuring a sample plot in Forest Reserve where no producer was present at the site. Then, another charcoal producer working nearby came to see what were doing and we interviewed him. However, his kiln was actually located on customary land, adjacent to the Forest Reserve.

hectare. The scientific name for each species was matched to the specific wood density obtained from a global database used in previous work (Pelletier et al., 2017). For stumps, we used two models based on the stump height and top diameter to estimate the dbh and the ground-level diameter. We used these diameter values to calculate the stump volume that we converted to biomass (Lauri Vesa et al., 2016). Using the estimated dbh for stumps, we estimated the aboveground and belowground biomass of trees before they were cut down for charcoal, by comparing allometric models developed in the miombo woodlands in Tanzania (Mugasha et al., 2013) and Zambia (Chidumayo, 2014). These equations were also used to estimate the aboveground and belowground biomass of trees left intact on sites. For woody debris, we calculated the volume of each piece of woody debris and converted it to biomass by applying a decay factor to differentiate between the biomass of sound and rotten wood. We provide the equations used in the biomass calculation in Appendix 1.

We calculated the biomass loss per site by estimating the full-tree biomass before charcoal production (from estimated dbh) and after (stump), assuming no change in belowground biomass. This assumption was used because all trees of the miombo woodlands can re-sprout from stumps and the stumps will stay alive after cutting if there is no further damage. We also assume that the coarse wood debris resulted from the charcoal production. This assumption is also justifiable because the vast majority of the wood found at the sites was sound (not rotten) and because in the miombo woodlands, bush fires have a return period of 1-3 years, burning most wood debris in its passage.

In terms of biodiversity impacts, we limited our analysis to tree species richness at the sites as an indicator but recognize that this is only one facet of biodiversity. With tree species identified during the inventory, we created a tree species abundance table for the sites and calculated tree species richness. We calculated the species abundance most frequently extracted based on stumps as well as the trees that remained standing on sites (not extracted). We compared the dbh distribution of standing trees before and after charcoal production.

Statistical analysis

With our statistical analysis, we looked for patterns by comparing conditions between land tenure types and by looking for relationships between variables that characterize charcoal producers at the sites that we visited.

For categorical data, we use the multivariate Chi-square (χ^2) test with permutations to look at the independence between two categorical variables, calculating the Freeman-Tukey statistics (Legendre and Legendre, 2012) that we compared with the critical value based on Sokal and Rohlf (1995). We use one-way analysis of variance (ANOVA) with permutation tests (Legendre, 2007), to look at difference among groups on a continuous variable, that was distributed normally or could be transformed. If the difference was significant, we used Tukey HSD multiple comparisons of means at 95% confidence level.

We used clustering methods with the survey to producers in order to identify gaps in the dataset that would allow us to distinguish different categories of charcoal producers or define typology. We compared different hierarchical (simple linkage, complete linkage, Unweighted Pair-Group Method using arithmetic Averages (UPGMA) and Ward) and non-hierarchical (K-means) clustering approaches using Gower dissimilarity index (distance) that represents well variables of different mathematical types (categorical, binary, and numeric) found in the survey (Borcard et al., 2011).

For each charcoal producers, we assessed the cash costs, revenues and net gains from their charcoal activities and calculated summary statistics on these reported values.

RESULTS

Impacts of charcoal production on the vegetation by land tenure type

In terms of general description, out of the 139 field plots located at charcoal kiln sites and that we surveyed, 35 were on customary land, 32 on private land and 72 on State land[4]. Almost all sites were in dry miombo woodland, with only 2 of 139 in *chipya* vegetation. Most of the sites were clear cut (n=107) rather than selectively logged (n=32), and only 2 plots had timber trees extracted from the sites prior to charcoal production while other plots did not. Current year fires were identified on 53% of the sites, all of them surface fires, 44% of the sites showed no evidence of fire and less than 3% had evidence of an older fire. The average distance to the farthest stump, an indication of the area of impact and of how far people will carry the logs, was 45 meters (m) from the kiln, with a maximum distance of 101m. We identified that 55% of the sites were cleared for energy purpose as the main driver, while 45% were cut with the purpose of farmland expansion, with charcoal generated as a byproduct. As we show below, we found patterns for several variables that correspond closely with the land tenure regime of the plots in question.

Overall, we found important differences among land tenure types in terms site conditions before and after charcoal production, as well as in terms of purpose for forest clearing. Before

[4] It was not possible to evaluate the total area of charcoal production per land tenure within the study area, among other reasons because there is no map of land area under private leasehold or customary lands, so this information has to be confirmed through field visit, as it was done in this study.

charcoal production, we found that sites on State land had significantly greater biomass before charcoal production than on private land, while it does not differ significantly for customary lands (F=6.92, p-value=0.003, Figure 2). We also found that tree species richness before charcoal was significantly higher on customary and State lands, compared to private lands (F=7.6, p-value=0.002, Figure 3). This indicates that from the start, sites on State Lands but also on customary lands had a higher number of tree species than on private lands. This coud indicate that the sites were more intact or it may also be a consequence of previous disturbances.

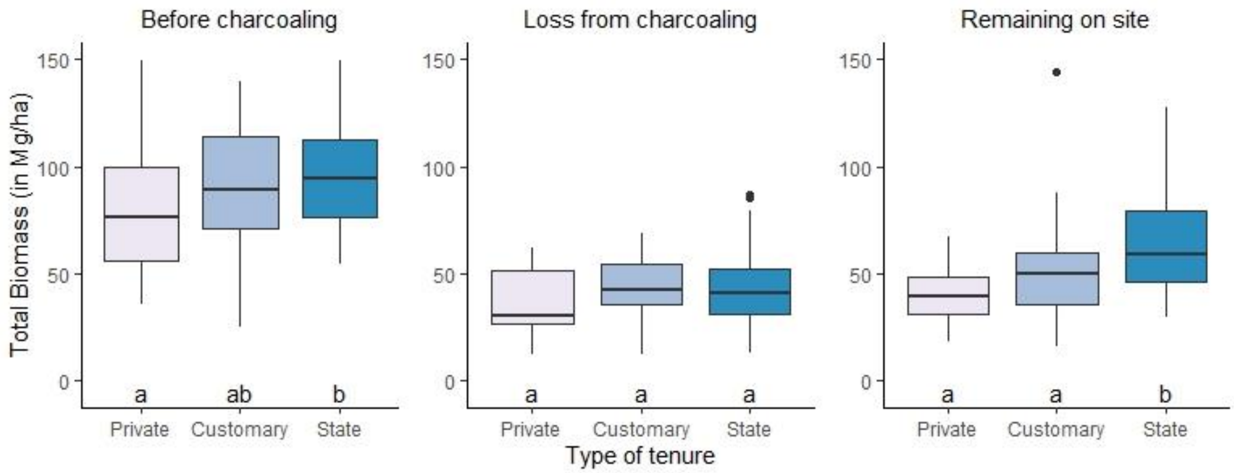

Figure 2. Boxplot of total biomass per land tenure type. We compare the biomass estimated before charcoal production (left), the biomass loss by charcoal production (middle) and the remaining biomass on site (right). The letters located above the x-axis indicate the results of Tukey HSD posthoc multiple comparison tests.

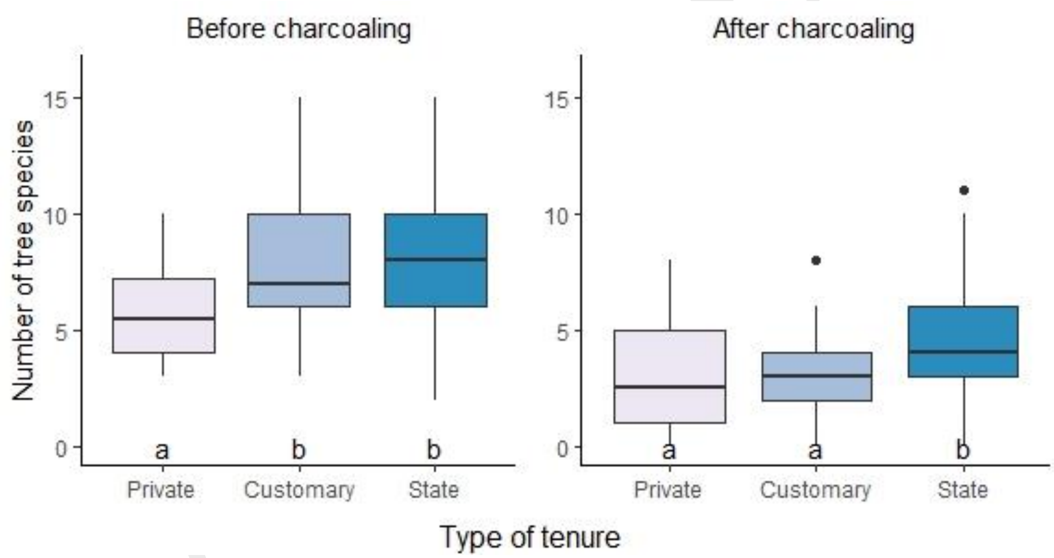

Figure 3. Tree species richness per site (of 1,257 m^2) before (left) and after (right) charcoaling by land tenure type. The letters located above the x-axis indicate the results of Tukey HSD posthoc multiple comparison tests.

Land tenure drives the purpose and methods of forest clearing (Table 1). On private and customary lands, charcoal is produced significantly more as a byproduct of agriculture expansion and significantly less for energy purposes (χ^2= 44.3, p-value=1e^{-04}). On State lands, however, forest is cleared significantly more solely for energy purposes; State land is significantly less frequently converted to agriculture. State lands were significant more likely to have experienced fire prior to charcoal production and significantly less likely to exhibit no sign of either recent or past fire, while private lands were just the opposite, each as compared to customary lands tenure (χ^2= 70.3, p-value=1e-04). Significantly more selective logging is taking place on customary land while significantly less is done on private land (χ^2= 12.9, p-value=0.002), possibly because more trees are left on farms in customary lands. Timber, medicinal and fruit trees are sometimes intentionally left standing when opening a field for agriculture.

Table 1. Freeman-Tukey statistics for differences by land tenure type

Driver of forest clearing				
	Customary	Private	State	Critical value
Charcoal production	**-2.23**	**-2.98**	**2.79**	1.79
Agriculture	**2.02**	**2.45**	**-4.07**	
Method of tree extraction				
	Customary	Private	State	Critical value
Clearcut	-1.16	1.25	-0.02	1.79
Selective	**1.85**	**-3.11**	0.16	
Fire occurrence				
	Customary	Private	State	Critical value
No fire	0.70	**3.84**	**-4.51**	2.55
Recent fire	-1.02	**-7.26**	**3.09**	
Old fire	1.28	-1.37	-0.22	

Note: The overall null hypothesis (H0: complete independence of the variables) had been rejected first, before testing the significance of the observed values in individual cells of the table. The statistics for Chi-square (χ^2) test of independence with permutations and p value are presented in the text. The cells report the Freeman-Tukey statistics among the three land tenure types and the categorical variable of interest, with a significance level of α=0.05. Values in bold are statistically significant compared to the critical value shown in the right column and calculated based on Sokal and Rohlf (1995).

Given these differences among land tenure types in the purpose and methods of land clearing, it follows naturally that the environmental footprint of charcoaling differed by land tenure regime. The mean biomass loss due to charcoal production was weakly significantly different among land tenure categories (F=3.2, p-value=0.05, Figure 2). State lands had significantly more biomass remaining on site after charcoaling than did customary or private land (F=9.0, p-value=0.001, Figure 2).

The estimated mean biomass before charcoal production within the sampled plots is of 113.5 ±41.8 tons/ha (Table 2). Charcoal production induced an average biomass loss of 56.8 ±22.8 tons/ha, which is equivalent to 27.9 ton of C/ha or 102.2 of ton CO_2/ha. The mean remaining biomass on site, composed mainly of stumps, belowground biomass, some trees left standing and coarse woody debris, was 60.5 ±31.2 tons/ha, so about half of the original biomass.

Table 2. Impacts of charcoal production on tree biomass and related emissions

	mean	**sd**	**min**	**median**	**Max**
Biomass ex ante (tons/ha)	113.5	41.8	27.7	109.8	284.0
Biomass loss (tons/ha)	56.9	22.8	14.8	55.0	127.9
Remaining biomass on site (tons/ha)	60.6	31.2	15.9	53.2	205.6
Carbon loss (tons of C/ha)	27.9	11.2	7.2	27.0	62.7
CO_2 loss (tons of CO_2/ha)	102.2	41.0	26.5	98.8	229.8
Biomass loss ratio	0.51	0.11	0.22	0.53	0.65

Charcoaling left differential environmental footprints not only in terms of biomass but also on tree species richness. Remaining tree species richness after charcoaling was significantly higher on State land than on customary or private land (F=7.6, p-value=0.002, Figure 3). All dominant miombo woodlands tree species were extracted, which in order of abundance include *Julbernardia paniculata*, *Brachystegia boehmii*, *B. longifolia*, and *B. spiciformis*, with noticeable change in species composition before and after extraction (remaining trees at the site) (Figure 4). The extraction was done along a broad range of dbh, with the few remaining trees after charcoal being mostly smaller than 25 cm dbh (Figure 5). So, generally, most tree species from all diameter size gets harvested for charcoal, without much specificity.

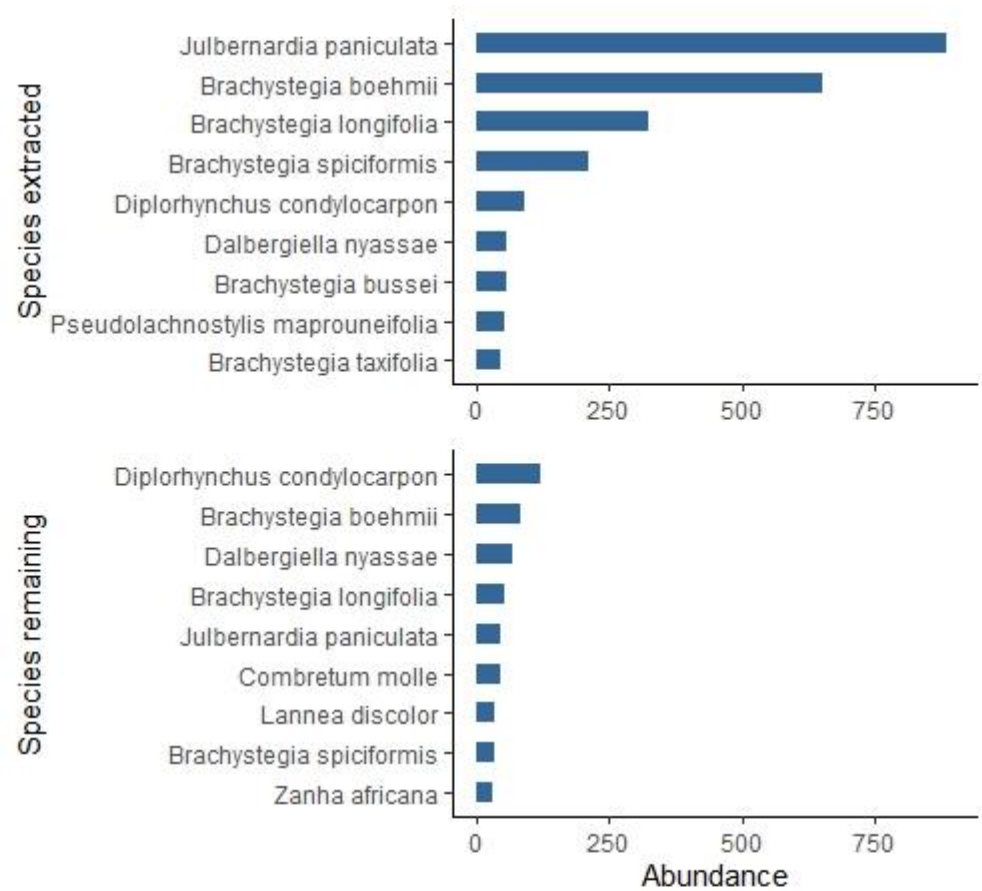

Figure 4. Abundance of tree species extracted (Number of stumps per tree species) (Upper panel) and abundance of tree species remaining on site after charcoaling (Lower panel).

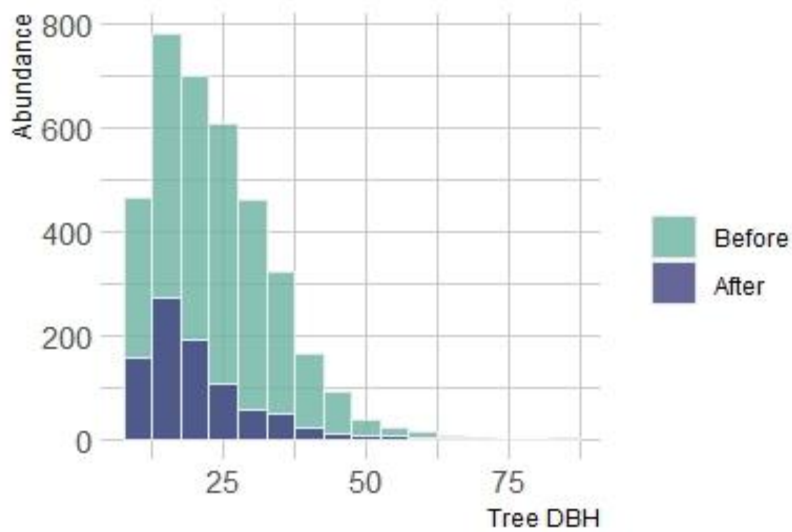

Figure 5. Tree dbh distribution before and after charcoal production. Each bin represents a 5cm range. Only trees dbh ≥ 10cm were measured. The dbh before extraction is estimated based on an allometric model including the stump diameter and stump height presented in Appendix.

The average charcoal production site covered almost half a hectare (0.46 ha), with a maximum area of about 2 hectares. The area impacted was significantly less on private lands (mean=0.25 ha) than on customary (0.66ha) or State (0.46ha) lands (F=14.3, p-value=0.001, Figure 6).

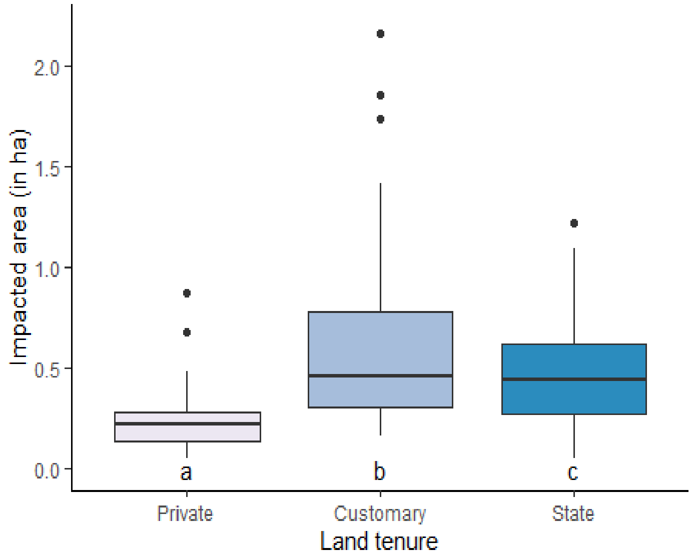

Figure 6. Charcoal impacted area in hectare by land tenure. The letters located above the x-axis indicate the result of Tukey HSD posthoc multiple comparison tests.

Overall, charcoal production results in a sizable loss of tree biomass and species richness. The purpose, methods, and environmental impacts of charcoaling differ markly by the tenurial regime of the cleared sites, and conform to incentives for the use of the land for agriculture in customary and private lands, as well as legal prohibitions of agriculture on State lands held in Forest Reserves.

Typology of charcoal producers

We surveyed 55 producers available at the production sites. Relative to the land area and biomass harvested, we surveyed more producers on private land (n=25) and customary land (n=17) than in Forest Reserves, meaning State land (n=13). This seems to reflect differences in legality across land tenure types and thus the social acceptability and legal risks of being caught producing charcoal in Forest Reserves. Many producers working on State lands were observed running away as the research team approached their charcoal production site.This underscores that our survey results should be interpreted with caution because of our small sample size and the opportunistic sampling. But rural household survey data may not provide a less biased view, since, as we show below, many charcoal producers came from Lusaka or other towns to produce charcoal and would not be sampled in a rural household survey. Unbiased characterization of the informal and generally illegal charcoal production and trading sector is difficult, so we emphasize the purely descriptive and imperfect nature of the results we report in this section.

Charcoal producers are a varied group, as we show below. But there are a few key things they have in common. Few – only thirty percent (Figure 7a) – have charcoal as their main source of income. Most are male (84%), some female (13%), or, rarely, husband and wife producing together (3%). Most producers have a spouse/partner and on average 4.5 children. Most producers started making charcoal about two years ago and have learned how to produce charcoal through friends. They overwhelmingly work alone in making charcoal, rather than in organized groups, consistent with prior observations (Kabisa et al., 2020; Mulenga et al., 2015; Vincent Ziba and Grouwels, 2017). When asked if they consider charcoal production a good economic opportunity for them or if they would rather be doing something else, all of them responded that they would rather be doing something else. Respondents overwhelmingly consider charcoal production too demanding, strenuous, unhealthy, and stressful, that it “reduces one’s lifespan”. Many considered that they would be doing anything other than charcoal if they had other alternatives to raise money. Many expressly indicated that farming is a better opportunity.

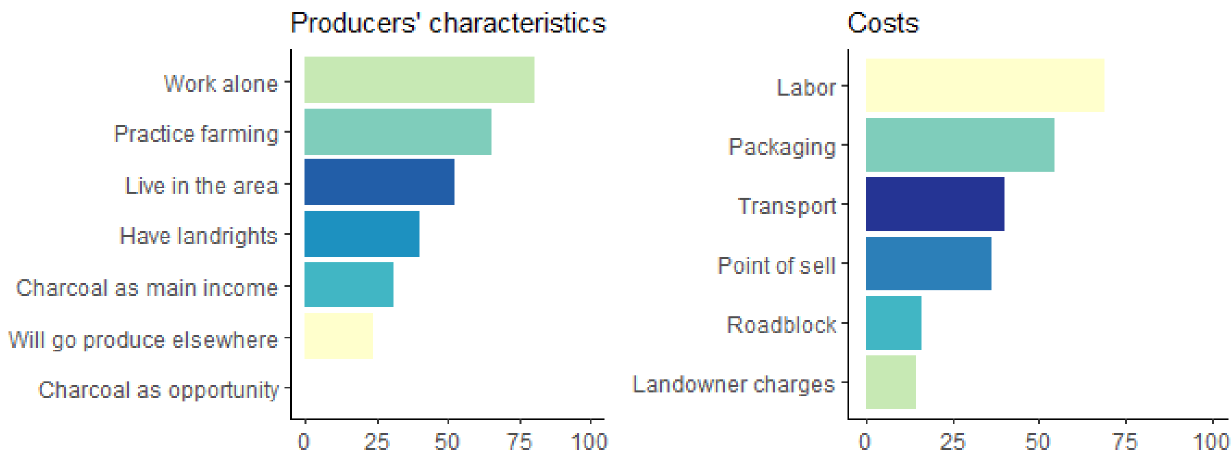

Figure 7. Barplots of the frequency in percent of a) different producers' characteristics and b) payment of costs involved in charcoal trading.

Coarsely, we can distinguish four main stylized types of charcoal producers. The first two groups of charcoal producers are mainly farmers (60% of respondents) cultivating maize, soy or cotton on customary and private lands and farming is their main source of income. Out of these farmers, one group produce charcoal on their own land. They may clear the trees to expand their farming area and produce charcoal as a byproduct and one-off source of income, perhaps because they have a larger landholding and/or trees on their land. These producers who produce charcoal on their own land will significant less frequently go elsewhere to produce charcoal (χ^2= 4.3, p-value=0.05) (Table 3).

Other farmers produce charcoal as complementary source of income during the off-farming season after harvest in May-June, for the dry season. During the dry season, which last from June to November, labor is available in rural Zambia because rain-fed farming is not possible. This enables them to devote time to charcoal production activity. They make charcoal in surrounding nearby Forest Reserves or on a (typically, wealthier) neighbors' land, providing tree clearing labor in exchange for the wood and space to make charcoal, with some land holder receiving a share of the charcoal or charcoal sales proceeds. Among this group, charcoal production is largely a way of capturing value from the wood that the land holder wants to clear away so as to enable cultivation or to use the wood in Forest Reserves close to their home. This group of farmers who live in the area are also significantly less likely to go produce elsewhere (χ^2= 10.5, p-value=0.002).

The third group of producers go to the forest expressly to make charcoal for sale and have charcoal as their main income source. With the off-season farmers group, this group encompass sixty percent of producers who do not have land rights where they are producing, so they work on others people's land (private leasehold or customary) or in Forest Reserves. For these two groups, charcoal production seems a way of tapping forests to add value to labor they would prefer to hire out for a wage or to employ in farming or other, less hazardous modes of self-employment. We found that producers that have charcoal as main source of income produced significantly less on their own land and significantly more on someone else's land (χ^2= 8.2, p-value=0.007). Notably, about half of the producers (47.5%) do not live in the area but rather come from Lusaka (25%), Mumbwa town (10%), Mazabuka (Southern Province) (7.5%) or another location (5%). A quarter of producers (24%) will go elsewhere to produce charcoal when the trees are cut down in the area where they were working and surveyed. For example, among this third group, we met a charcoal producer coming from another region that had obtained authorization by traditional authorities for clearing forests for agriculture but had no intention to cultivate the land, only to produce charcoal and move on somewhere else to produce. We found that those who do not live in the area will significantly more frequently go produce elsewhere when the trees are cut down in the area (Table 3). Many are urban in-migrants who return to rural areas to make charcoal they then bring home to sell in the town or city.

The fourth group is for the small number of producers that earn their livelihood mainly as business owners (4%), or service workers – e.g., civil servants (6%). Most of them do not live in the study area and all of them sell their charcoal directly to consumers, possibly because they have the funds to pay the associated costs.

Table 3. Freeman-Tukey statistics for differences among producers.

Main income & land rights		
	Have landrights where they produce	
	No	Yes
Other income	-1.00	1.19
Charcoal	**1.41**	**-2.16**
Main income & after where		
	Will go produce elsewhere when trees are cut down in the area	
	No	Yes
Other income	0.93	**-1.84**
Charcoal	**-1.45**	**2.03**
Landright & after where		
	Will go produce elsewhere when trees are cut down in the area	
	No	Yes
No landrights	-0.60	1.11
Landrights	0.80	**-1.52**
Living & after where		
	Will go produce elsewhere when trees are cut down in the area	
	No	Yes
Lives in the area	1.09	**-3.25**
Lives elsewhere	-1.06	**1.70**
Critical value :	1.25	

Note: The overall null hypothesis (H0: complete independence of the variables had been rejected first, before testing the significance of the observed values in individual cells of the table. The statistics for Chi-square (χ^2) test of independence with permutations and p value are presented in the text. The cells report the Freeman-Tukey statistics among producers' characteristics, with a significance level of α=0.05. Values in bold are statistically significant compared to the critical value shown on the last row and calculated following Sokal and Rohlf (1995).

All the clustering methods we tried separate the producers into two main groups that reflects the trading strategy they employ to sell their charcoal: 1) sell to buyers (intermediaries) or 2) sell directly to consumers (without intermediary). About half of the surveyed producers sell their charcoal to buyers that come to purchase at rural production sites, while the rest of producers sell their production by themselves, mostly in Lusaka (38%) or in Mumbwa town (11%); a small minority use both strategies (9%). The complete linkage clustering method similarly separates producers into three groups, by dividing those who sell by themselves between those who sell locally (e.g., in Mumbwa town), often transporting their charcoal by bicycle, from those who sell in Lusaka. This separation of producers according to the trading strategy indicates that the choice affects several variables that we assessed with the survey.

Even omitting unpaid labor due to likely measurement error in self-reporting of effort and difficulties in properly valuing that time, labor is the most frequent cash expense charcoal producers incur (Figure 7b). Much of this is small payments for assistance loading/offlading charcoal bags, etc.

As one would expect, those who sell by themselves directly to urban consumers incur significantly higher costs (F=18.7, p-value=0.001, Figure 8a). On average, the producers that sell by themselves to consumers invest 10 times more money than do those who sell to buyers at the production sites (Table 4).

Among the costs that selling charcoal directly to the market entails, we found that transportation by truck constitutes that highest cost, typically 25-50 Zambian Kwacha (K) per bag.[5] Other costs include charges at roadblocks held by police officers, labor for unloading the

[5] Our survey included a question asking if the producer pay for permits and, if yes, the cost of permits. 47.3% claimed they paid for permit, mostly for conveyance, but rarely for a production permit. Others said that buyers and truck drivers buy the permits. The reported costs varied wildly –from K100 to K4500, or K50 per bag, which exceeds the average price fetched for a 50kg bag (Table 4). We ignore permit costs because we rather doubt many of those who claimed they paid for permits actually did, not least of which because if we included permit costs, those producers that claimed they purchased a permit

bags at the market, and marketplace fees. Packaging costs for charcoal (including bags and ropes) are paid by all producers. But some buyers provide those (relatively inexpensive) inputs to producers who produce charcoal for them. On private and customary lands, producers sometimes pay or give part of their production to the owner of private land or to the headman on customary land. Some charcoal producers – especially farmers making charcoal as a byproduct of agricultural land conversion – pay for labor (cutting trees, stacking the kiln). Some producers also reciprocate by helping one another on their own kiln or through a *mbile* or work party, where the host provides food and drink in exchange for help with their work. While our data do not allow us to account for the value of the time that producers invest themselves, cash expenditures are quite modest for those charcoal producers who sell to buyers at the site, while those who sell directly to urban consumers, without intermediary, transport costs and other cash expenditures are substantial. We did not include a specific question about tools, such as axes and shovels, which are used by all charcoal producers, but are not used mainly much less exclusively in charcoal production. We may therefore slightly underestimate total production costs. Figure 8 shows the percent of producers that pay each of the costs mentioned.

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would have incurred substantial cash losses. That seems unlikely, especially since we observed them producing charcoal again. The price for the production license is K270 per cord of wood (3 cubic meters, which is equivalent to 10 50kg-bags). The conveyance permit is valued at K13.50 per bag.

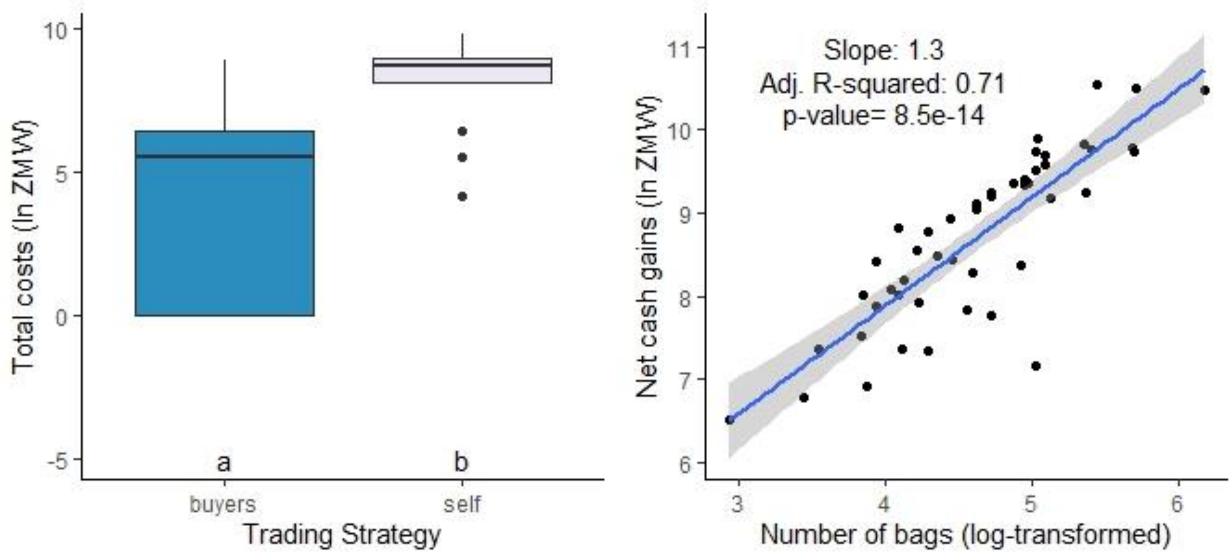

Figure 8. Costs and gains for charcoal producers. In the left panel, we compare the total costs of production between trading strategies and found a significant difference using one-way ANOVA with permutation test (Legendre, 2007). In the right panel, the relationship between the net gain and the number of bags produced is presented.

Table 4. Average annual cash costs, revenues, and net cash gains (cash revenues minus cash costs) by charcoal trading strategies for producers. Amounts are in Zambian Kwacha.

Trading strategy	Costs	Revenues	Net gain	Standard deviation net gain	Minimum net gain	Maximum net gain
Sell to buyers	678	9,635	8,957	7,754	750	35,400
Sell by themselves	5,885	15,735	9,850	10,770	675	38,350

The motivation for charcoal producers to market directly is the higher prices they receive. Table 4 shows that both for 50 kg (F=4.2, p-value=0.03) and 90kg bags (F=17.4, p-value=0.001), direct sales to consumers fetch an average premium of 41-106 percent (Table 5). The lowest prices for bags sold directly to consumers in urban areas almost always exceeded the highest price received by producers selling directly to intermediaries.

On average, producers' net cash gains from direct-to-consumer sales are only K893 (10 percent) higher and not statistically significantly different from those who sell to intermediaries. Net cash gains from charcoal production increase statistically significantly, at a roughly constant rate, in the total number of bags produced and the net cash gain (Adjusted R^2=0.71, p-value=$8.5e^{-14}$, Figure 8b). So the financial incentive to direct market is low, favoring those – largely urban residents – who would go back and forth between urban markets and rural charcoal production sites anyway, for whom the marginal costs of time spent in transit and sales are negligible. We also found that producers for whom charcoal is their main source of income are not significantly more likely to sell it by themselves (χ^2= 0.45, p-value=0.84) nor to produce more charcoal in terms of total production (F=0.54, p-value=0.45).

Table 5. Mean of the average, low and high prices for two charcoal bag sizes received by charcoal producers surveyed. Amounts are in Zambian Kwacha.

	Price for 50kg bag			**Price for 90kg bag**		
Trading strategy	Average	Low	High	Average	Low	High
Sell to buyers	44	34	48	68	57	77
Sell by themselves	62	45	71	140	100	193

Note: The 50kg bag and the 90kg bag refer a typical volume of charcoal traded rather than mass of charcoal. The reason is that producers use maize bag for 50kg or 90kg of maize.

Tying the producer survey results back to the environmental footprint findings, we found only weak relationships, none of them statistically significant.[6] Average net cash gains are slightly higher on customary lands than on State and private lands. We also observed the largest kilns on customary lands, especially in a 'farm block' area endorsed by the Zambian government for agriculture expansion. Producers on customary lands also sell more to buyers and less directly to consumers in towns. Net gains are more variable on private lands, where producers appear to sell by themselves more frequently. We also observe higher mean biomass loss for those producers that said they will go elsewhere to produce charcoal once the trees are all cut down in the area where they work. There is of course a positive relationship between the amount the charcoal produced and the area impacted (Sedano et al., 2016), so higher net cash gains signify a larger area of woodlands impacted by charcoal production.

IMPLICATIONS FOR SUSTAINABLE ENERGY TRANSITIONS

We examine the charcoal production landscape to inform deliberations around transitions towards sustainable energy. We present both biophysical and social characteristics from a hot spot production area of Zambia and by focusing on the role land tenure and labor markets play in shaping the environmental footprint of this industry. We link these findings with the regional context, highlighting similarities and differences with other studies, to orient policy for the

[6] Since the survey to producer was conducted using an opportunistic approach, the kiln sites and the producer did not always match, which likely explain why no significant relationship between the sites and the producers was found.

'greening' of the charcoal value chain in ways that might improve forest resources management, sustain future energy supply, and improve rural livelihoods.

Land tenure as a key structuring factor

A clear implication of the patterns we observe is that land tenure structures distinct pathways of forest clearing for charcoal production. On private and customary lands, we found that the main driver of forest clearing is the demand for agricultural lands. On these lands, the situation is similar to the situation in Tanzania, where a recent study shows that agriculture is the main driver in 81% of cases, while charcoal is the main culprit is 12% of cases (Doggart et al., 2020a).

Conversely, we found that on State lands, which includes Forest Reserves, forest is mainly cleared for the express purpose of making charcoal to satisfy burgeoning urban energy demand. Regionally, charcoal is the main driver of forest (or woody biomass) loss in areas where the land is less propicious to agriculture due lower rainfall, including in Southern Mozambique (Mabalane) (Sedano et al., 2020, 2016) and in Somalia (Bolognesi et al., 2015; Rembold et al., 2013).

Different land tenure arrangements generate different land use incentives. For example, previous work has shown that land tenure arrangements influence farmers' choice to invest in soil management practices and conservation measures, and that more secure tenure stimulates productivity-enhancing investments in agriculture (Abdulai et al., 2011; Domeher and Abdulai, 2012). Environmental constraints related to rainfall variability, affect households' decisions and strategies to manage risks (Kalkuhl et al., 2020). In the context of this study, we saw that land tenure, including protected status, influences land use choices related to charcoal production. On State lands and especially Forest Reserves, where agricultural cultivation is prohibited, charcoal is the main driver of forest loss.

To the best of our knowledge, this is the first time that land tenure is identified as a key factor affecting charcoal production. We show below that these different pathways of impacts act in concert to produce charcoal's environmental footprint and also condition the appropriate response for transforming the charcoal value chain.

Charcoal as a driver of forest loss

When forests are cleared to produce charcoal, then urban charcoal demand becomes a driver of forest degradation and of additional GHG emissions, even if there is no permanent change in land use. The environmental footprint of the activity depends on the harvesting intensity, that is the number of the tree species and the tree size extracted, which can be more or less selective. The woodland or forest type also matter because some of these ecosystems show more resilience to anthropogenic disturbance than others. The sustainability of extraction can be evaluated by comparing the rate of forest regrowth and the time needed to recover to pre-existing conditions.

Due to these characteristics, the charcoal industry's environmental footprint may vary spatially across southern Africa. In Mozambique, a recent study found that most ecosystem services they measured remained available because charcoal is produced at low intensity, with the selective harvesting of Mopane trees (*Colophospermum mopane*), mostly from the larger diameter size trees (Woollen et al., 2016). The mopane tree is considered superior for charcoal-making. The authors signal that to reduce future impacts of charcoal production, producers must not expand extraction to other tree species and to smaller tree sizes.

We found that on State Land, in particular in Forest Reserves, where charcoal is the main driver of forest clearing, the woodlands generally had higher carbon stocks and tree species richness, but were being heavily impacted by charcoal production. Illegal extraction in Forest

Reserves can have long-term consequences because charcoal production is done with high harvesting intensity. Miombo tree species, and of all sizes (> 10cm dbh), are extracted to make charcoal, even when there is no change in land use and so extraction is far less selective than in the mopane woodlands of Mozambique. Unfortunately, forest regeneration is slow in the dry miombo woodlands. Chidumayo (2019) recently showed that the predicted cord wood accumulation of re-growth after charcoal production in the dry miombo plateaus after about 25 years at lower levels than before extraction, which makes charcoal production unsustainable.

It is important to consider that the social dynamics that creates the harvesting intensity may change over time too. The confluence of urbanization, population growth, agriculture expansion and climate change that affect both energy provision from hydroelectricity and the productivity of agriculture may certainly increase the pressure on unmanaged/unprotected forests and woodlands. Degradation of forest resources and land-use change have been shown to affect rural and urban consumers who had to rely on lower quality fuel in Uganda, with negative health outcomes (Jagger and Kittner, 2017; Jagger and Shively, 2014) or spend more time or/and money for fuel in Malawi (Jagger and Perez-Heydrich, 2016).

Regulatory oversight

There will be limited incentive to produce charcoal legally until there is a cost for producing illegally and that the risks of getting caught surpass the benefits of producing without license. Sustainable charcoal production hinges on enforcement of laws regulating charcoal production and conveyance.

In Zambia, the Forestry Department is the governmental entity accountable for the supervision and management of forests resources under the Forest Act 2015. The weak enforcement of charcoal licenses and permits has been associated in previous studies with a lack of funding for staff in forestry offices as well as vehicles at the provincial and district level to patrol, monitor and enforce regulations (Gumbo et al., 2013; Kabisa et al., 2020). The monitoring and enforcement of licenses and permits is a crucial building block for formalizing the industry and controlling access to forest resources, on State and customary lands. Revenues collected from permits and licenses are currently insufficient to re-invest in sustainable forest management and energy transitions, seemingly trapping the Department in a low-level equilibrium of weak enforcement and anemic funding.

Due to the lack of enforcement and presence in Forest Reserves where we worked, including Lutale, Mumba and Sanje Forest Reserves, the miombo woodlands are getting vigorously cut down and degraded. The extraction benefits producers, but is unsustainable for the reasons explained already. Charcoal production is quickly produced compared to crop cultivation, thus easy to evade detection, especially by an under-resourced state agency struggling to enforce its own rules. Without adequate rules enforcement by the Forestry Department – which itself depends on adequate funding to establish a virtuous cycle of licensing and permit fees that finance enforcement – the prospects seem low for State lands to sustainably support expanding urban demand for charcoal in the Lusaka area. Increasing production costs through a regulated charcoal value chain, may increase the price of the charcoal for consumers, which may make alternative fuel more competitive and/or require some subsidy for vulnerable households, as previous research as shown the strong influence of the price on household fuel choices (Doggart et al., 2020b; Mulenga et al., 2019).

Agriculture as the main driver of deforestation

Agriculture is the main driver of forest loss on customary and private lands, with implications for the environmental footprint. In our survey, 74% of charcoal production sites on customary and private land are converted to agriculture. Deforestation in Tanzania, dominated by miombo woodlands, is also driven by agriculture expansion, with smallholder farmers moving to forested areas to access better farmland (Doggart et al., 2020a).

Land-use conversion has more permanent consequences on forest carbon stocks and biodiversity because cultivated lands rarely revert back to forest in this setting. Indeed, we may have underestimated carbon loss at sites converted to agriculture, especially if farmers burn or remove the stumps from the fields which could otherwise regenerate by coppicing (Luoga et al., 2004), and/or if they plough the soil which removes saplings (Chidumayo et al., 1997), thereby further reducing regeneration potential. The production of charcoal as a byproduct of agricultural land conversion does not produce significant additional GHG emissions, however, as the trees would have been removed anyway. Charcoal is just the means of disposing of the cleared biomass. Deforested land converted to agriculture is however out of commission for producing charcoal for the forseeable future, thus, as a result, not a sustainable source of charcoal for urban consumers.

The implications of agricultural expansion with charcoal as a byproduct are manyfold. It means that even if charcoal consumption would stop tomorrow, forest resources would still be under threat. Thus, acting on the demand side alone, by subsidizing alternative fuels or promoting improved cookstoves - important ingredients of an energy transition and desirable for stemming indoor air pollution and respiratory ailments – may have limited overall impact for ‘greening’ the charcoal value chain because a large part of the charcoal is produced as a byproduct of cropland expansion. Part of the solution must therefore come from the agricultural sector.

Slowing deforestation depends on changes in agricultural practices that stem deforestation. Recent research finds a strong negative association between uptake of improved (hybrid) maize seed on adequately fertile (i.e., non-acidic) soils and deforestation, an effect that is reinforced when combined with inorganic fertilizer adoption (Pelletier et al. 2020), echoing recent findings from Malawi (Abman and Carney 2020). One path to reduced deforestation runs through efforts to encourage sustainable agricultural intensification and boost employment and rural wages.

Labor market conditions

Although we observe that land tenure type clearly influences land use patterns and thus the drivers and environmental footprint of charcoal, charcoal production and trade seems related as much by labor market conditions as by land access. The “greening” the charcoal value chain could pass by policies that impact the labor markets by driving up the cost of tree clearing.

The availability of underemployed or unemployed labor – either outside the active agricultural period, in the dry season, or in labor surplus households, including those at some distance from the farm and urban areas– provides an additional incentive to convert forest to agriculture, as evidenced by the fact that most producers do not make charcoal on their own land in our study area. Charcoal producers do the hard work of removing the trees, a benefit for the landowner who plans to cultivate the plot in the future.

Although this work is clearly undesirable according to the producers’ viewpoint, we found that some dedicate themselves to charcoal-making and obtain most of their income from this activity. Yet, most use it mainly as an income supplement, including especially farmers who welcome this added source of cash income during the dry season or when they bring new land into cultivation. The lack of enforcement of license and protected area land use rules, combined with proximity to the capital city, gives producers flexibility to select their trading strategy, including to sell directly to markets in Lusaka or to intermediaries who collect charcoal near rural production sites. The fact that there is no significant difference in profitability between strategies signals that entry into either is reasonably unrestricted. The subsample of producers who work on others' or State lands to produce charcoal are clearly driven into this work by weak labor market conditions. As a result, a diverse set of producers, including both rural and urban dwellers, actively participate in charcoal-making, which offers an option to make money in a context where few other employment alternatives exist.

Investments in sustainable intensification that could create employment and raise rural wages would increase the costs of forest clearing. One share of rural charcoal producers that make charcoal during the extended dry season could also move away from the charcoal business if they could adopt irrigated agriculture or permanent agriculture (e.g. agroforestry), that could lock their time into productive activities year round. Professionalizing charcoal producers through community forest enterprises and producer organizations can also be a response to the weak labor market conditions.

Community forest enterprises

The creation of community forest enterprises holds potential for transforming the charcoal value chain. Promoting the formation of Community forest enterprises, community forest management (CFM) groups or producer organizations may have multiple benefits. It can help create jobs in rural areas. It is one way to include poor and casual producers that individually could not pay for licenses, in a context where the system is regulated. These groups can be supported by state extension services providing sustainable forest management training, access to modern kiln technologies that convert wood to charcoal more efficiently, in developing rules to respond to demand for land-based activities, including expansion of farming and charcoal production, as well as developing forest management plans. We consider the formalized management, clear rights and multi-function sustainable harvesting plans constitute elements that may deliver sustainable production.

In principle, customary lands could be a good avenue for strengthening local forest management, a governance and management approach where communities can establish and enforce rules to sustainably manage common property resources (Ostrom, 1999, 1990). Customary lands harbor woodlands with high forest carbon stocks and tree species richness in our case study area and the extraction is significantly more selective than on private lands. There is a large body of evidence to support CFM to improve forest conditions worldwide (Pelletier et al., 2016). Even though the causal linkages between devolved forest rights and improved forest conditions remains unclear (Yin et al., 2016), it is thought that people having long term stake in sustainable forest production are more amenable to invest their time and energy to use the resource sparingly.

Tanzania is one country that has developed a long term experience with community forest management (Blomley et al., 2008; Lund et al., 2015; Lund and Treue, 2008; Mukama et al., 2012; Treue et al., 2014; Vyamana, 2009). However, the country is also trying to develop community-based approaches relevant to the charcoal context, a more intensively extractive industry that is more complex to manage than the typical subsistence-based forest products extraction. In other countries, including Mozambique, the charcoal trade is rather dominated by large-scale operators who can obtain commercialization rights, while local communities struggle to integrate the value chain and derive local benefits (Baumert et al., 2016).

Past experiences in Zambia with Joint Forest Management (JFM) however did not incentivize local participation in forest conservation, mainly because it focused on the non-economic benefits of forest conservation and lacked the legal framework for sharing management and revenues with the community (Phiri et al., 2012; Contestabile, 2014; Leventon et al., 2014).

In Zambia, traditional institutions are already legally recognized in the Land Act for regulating access to land, including forestland, on about 51-54% of the country's land area (Sitko and Chamberlin, 2016). And some do effectively impose restrictions on forest use. For example, traditional authorities in our case study area prohibit the use of chainsaws to cut trees and that prohibition seems to work in general. A previous study found that in their current state, however, local forest management institutions in customary areas, given their informal rules and a lack of enforcement structures, were largely ineffective at internalizing the costs of forest resources from depletion, especially for charcoal production (Mulenga et al., 2015).

Since then, the Zambian government has taken steps to further decentralize and devolve forest management to communities, for instance by adopting the Community Forest Management (CFM) Regulations of 2018 that promote CFM on customary and State lands (GOZ, 2018). The 2018 regulation facilitate formalization and strengthening of local forest management institutions by calling for the creation of community forest management groups, approved by customary institutions. The local CFM group has the exclusive use of the area and the ability to restrict access to outsiders, as well as the ability to issue community permits and collect revenue for products specified in the CFM plan.

Recent pilot projects for organizing charcoal producer groups provide a positive experience for improving forest management, that can take place within the same legal framework in Zambia (Kabisa et al., 2020; Vincent Ziba and Grouwels, 2017) and in the context of community forest enterprise in Tanzania, with the 'Conserving Forests through sustainable, forest-based Enterprise Support' project (CoForEST) (TFCG, 2021). The capacity of community-based management approaches to lead to sustainable management of forests and providing good rural wages is an important research item for a transformation of the charcoal supply chain.

CONCLUSIONS

Many SSA countries rely on forests and woodlands as their primary energy supply. Charcoal production plays a major role in their energy portfolio but its importance is not necessarily reflected in energy policy.

In this study, we looked at the supply side of charcoal production to inform a transformation towards a sustainable charcoal value chain. The field research located in a hot spot charcoal production area of Zambia serving the capital city of Lusaka shows that the environmental impacts of the growing charcoal industry varies by land tenure regime. Charcoal production on private and communal lands is largely a byproduct of land conversion for agriculture, thus is driven by broader incentives for agricultural expansion. Charcoal-specific policies cannot easily stem or slow charcoal production on lands under private or customary control without addressing incentives to convert forested lands for agricultural production. One policy option is to make deforestation more expensive through labor market interventions to absorb under- and un-employed labor that now works in charcoal production. Another key implication is that this portion of the charcoal throughput supporting rising urban energy demand appears unsustainable because little converted land to agriculture will regenerate to produce wood for charcoal again in the future.

In principle, land that is not converted to agriculture, as on State lands, including Forest Reserves and other protected areas – seemingly offer more potential to manage forests for sustainable charcoal yield. However, these protected areas were set aside for purposes other than charcoal production. These areas host woodlands with higher biomass and tree species richness than on customary and private lands. Weak state capacity presently limits enforcement of existing prohibitions on unlicensed charcoal production, however. This leaves State protected areas as effectively an open access resource for underemployed persons to exploit in hazardous work that helps them meet livelihood needs. The slow regeneration of these dry miombo woodlands, however, means that this stream of the charcoal trade likewise seems unsustainable, given the absence of either labor market interventions to absorb surplus labor or more effective enforcement of existing restrictions so as to reduce pressure on the forest.

The greatest promise seems to lie in improved common property management of customary lands by enforcement and devolution of local forest management to organized community forest enterprises or producer groups. More fundamentally, however, charcoal seems an unsustainable energy source to meet growing urban demand because the charcoal produced now come from lands under cultivation, where forest will not regrow, and dry miombo woodlands recovery rates are slow on remaining forestlands. Therefore, efforts to manage rising energy demand in Lusaka and similar SSA urban environments are likely best focused on transitioning consumers to other, more sustainable (but still affordable) energy sources for cooking so as to reduce the unsustainable demand for charcoal, but this alone will not save forests from threats due to agriculture expansion. Sustainable forest management should be an integral part of the national energy policy and the policy attention should reflect the role of wood fuel in the primary energy supply. Fundamentally, this work echoes the call for inter-sectorial approach between land, agriculture, forestry, and energy policies and institutions (Doggart et al., 2020a).

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Appendix 1: Biomass Calculation

Biomass for stumps and remaining trees

DBH before felling (stumps) To estimate tree biomass before charcoal production, we need to estimate the diameter-at-breast-height (dbh, 1.3 meter) of the stumps before felling. To do so, we used a model that relates the stump diameter at different heights to the dbh of the tree (Equation 1; *Source: Equation 1 was developed by L. Vesa in 2013 and is based on 32,000 live tree data collected with the NAFORMA Project in Tanzania supported by FAO. The model is provided in Vesa et al. (2016)*).

Equation 1:

$$dbh_{est} = d_{stump} + 0.38524 * (1.3 - h_{stump} - 0.20325 * (1.3 - h_{stump}) * d_{stump}$$

where dbhest = estimated dbh in cm, dstump = recorded stump diameter in cm, hstump = recorded stump height in m.

Diameter at the ground level (stumps)

The previous model's output is applied to compute stump diameter at the ground level.

Equation 2 (Vesa et al. 2016):

$$d0_{stump} = (dbh_{est} - 0.38524 * 1.3)/(1 - 0.20325 * 1.3)$$

where dbhest: estimated dbh in cm from Equation 1, d0stump: stump diameter diameter at ground level in cm.

Estimation of stump biomass by the stump volume

Two volume equations were compared based on different assumption about the shape of the tree.

Equation 3 for stump volume in cubic meter:

$$vol1_{stump} = ((\pi * (h_{stump}/100)/12) * ((d0_{stump}/100)^2 + ((d0stump/100) * (d_{stump}/100)) + (d_{stump}/100)^2))$$

Equation 4 for stump volume in cubic meter:

$$vol2_{stump} = ((\pi * (d0_{stump}/200)^2 + \pi * (d_{stump}/200)^2)/2) * (h_{stump}/100)$$

Conversion of volume to biomass using the wood specific gravity (wsg) that is tree volume in cubic meter multiplied by wsg in kg/m^3, equation 5:

$$AGB_{stump} = vol_{stump} * wsg_{stump}$$

Calculating biomass of stump before felling and for remaining trees, using estimated dbh for stump and the field measured dbh for tree left standing at the site.

Allomeric equation developed by Chidumayo *Environmental Conservation* (2013), without height parameter.

Aboveground Biomass, equation 6:

$$AGB_1 = exp(2.5553 * log(dbh) - 2.5265) * 0.001$$

where dbh = estimated dbh for stumps or dbh for remaining trees [cm], and 0.001 is the conversion factor from kilograms to metric ton, also applied below.

Belowground biomass, equation 7:

$$BGB_1 = exp(2.1712 * log(dbh)) - 1.9439) * 0.001$$

Allomeric equation developed by Mugasha et al. (2013), without height parameter.

Aboveground biomass, equation 8:

$$AGB_2 = 0.1027 * (dbh)^{2.4798} * 0.001$$

Belowground biomass, equation 9:

$$BGB_2 = 0.2113 * (dbh)^{1.9838} * 0.001$$

Stump and tree biomass per plot

After obtaining the individual AGB and BGB of stump, the estimated AGB before felling (the BGB remains the same) as well as the AGB and BGB of tree left standing at the site, we sum it up per plot and divide by the plot area ($\pi * r^2$) in square meter, converting the value to hectare, in order to obtain the biomass density in Mg/ha. Calculation is done separately for the AGB and BGB components of stumps, remaining trees, and trees before felling estimated from stump mensuration.

Biomass for woody debris

Volume equation for a Frustum (conical cylinder) in cubic meter (Vesa et al., 2016).

Wood debris volume, Equation 10:

$$vol_{wd} < -(\pi * (Diameter1_{wd}/200)^2 + \pi * (Diameter2_{wd}/200)^2)/2) * Length_{wd}/100)$$

where diameter1 = diameter of first end of the wood debris and, diameter2 = diameter of second end of the wood debris.

Including a decay factor (burned logged are counted as sound)

Decay factor (df) for wood debris is equal to 1 for sound wood and equal to 0.5 for rotten wood.

$$biomass_{wd} = vol_{wd} * wsg_{wd} * df_{wd}$$

where the woody debris volume in cubic meter multiplied by wsg in kg/m ^{3}.

The total woody debris per plot summed up and divide by the area of the subplot ($\pi * r^2/4$) in square meter and converted to hectare in- Mg/ha.

Calculating total biomass and loss from charcoal production

Different scenarios were calculated based the different models tested. Here, we present the information for one scenario to demonstrate our approach.

Estimated biomass before charcoal:

$$Biomass_{before} = AGB_{estfromstump} + BGB_{estfromstump} + AGB_{tree} + BGB_{tree}$$

where the AGB and BGB for stumps is calculated from the estimated dbh for stump to obtain the pre-felling biomass. It assumes no woody debris present at the site before charcoal.

Remaining biomass on site:

$$Biomass_{remaining} = AGB_{stump} + BGB_{estfromstump} + AGB_{tree} + BGB_{tree} + biomass_{wd}$$

where we account for the stump aboveground biomass but keep the same belowground biomass information.

Biomass loss from charcoaling:

$$Biomass_{Loss} = Biomass_{before} - Biomass_{remaining}$$

Conversion from biomass to ton of carbon per hectare:

$$C_{Loss} = Biomass_{Loss} * 0.49$$

Conversion from carbon to CO2 emissions with molecular mass:

$$CO_{2Loss} = C_{Loss} * (44/12)$$

Appendix 2: Financial costs, revenus and net gains

Because of the complex way that people integrate charcoal in their livelihood, it was not possible to provide a safe estimate of the time that producer dedicate to charcoal making. We provide however this assessment of the cash expenses and income generated from charcoal production as one starting point of information to understand the motivations for charcoal production. We estimated the annual cash costs, revenus and net gains because it simplified the comparison between producers, with some making one large kiln per year, while other make multiple smaller kilns.

Cash costs of producing charcoal

Expenses from charcoal producers were expressed using very different units that we had to bring to comparable units of measurement. Some expenses were reported as one time costs (e.g. Charcoal producer pay k4,000 for the truck to transport his/her charcoal bags to Lusaka), per bag, per activity, per day or week, per person, per hectares or per kiln. We had to adjust all these different units in a systematic way to enable comparison between producers.

For example, when the costs were expressed per kiln, we calculated the yearly amount we multiplied the cost per kiln by the number of kilns made by this producers.
Other example, one producer reported paying landowner per hectare. Since the producer produced two kilns for the year and that the average kiln size impacts 0.5 hectare of woodlands, we assumed one payment to the landowner. These examples show that some of the costs reported by producers had to be adjusted on a case by case basis.
We did not include the costs of charcoal production and conveyance licenses, or from shovels and axes. More information about this is provided in the main text.

This equation was used to calculated the total cost per producer:

$$\begin{aligned} Costs_{total} = (&Cost_{landowner} + Cost_{Labor} + Cost_{otherlabor} + Cost_{packaging} \\ &+ Cost_{roadblocks} + Cost_{transport} + Cost_{selling}) + \\ &Nb_{50kgbags} * (Clandowner_{\text{per50kgbag}} + CLabor_{per50kgbag} + COtherLabor_{per50kgbag} \\ &+ Cpackaging_{per50kgbag} + Croadblocks_{per50kgbag} + Ctransport_{per50kgbag} + CSelling_{per50kgbag}) + \\ &Nb_{90kgbags} * (Clandowner_{per90kgbag} + CLabor_{per90kgbag} + COtherLabor_{per90kgbag} \\ &+ Cpackaging_{per90kgbag} + Ctransport_{per90kgbag} + CSelling_{per90kgbag}) + \\ &(Time_{month} * 30 * 0.25 * Nb_{Kiln} * CLabor_{perDay}) + \\ &(Days * CSelling_{perDay})) \end{aligned}$$

– In some cases prior adjustment was made before being able to apply this calculation.
– The first part of the equation is the lump one-time reported costs. It was not always clear if the producer more than one truck and roadblocks fees per year. We assume one main trip to the city for selling charcoal.
– For labor costs, when the charcoal producer hire someone for a specific task, it is not equivalent to the time it takes for making the kiln. For this employees we assumed 1/4 of the time required per kiln, multiplied by the number kilns made.
– For selling costs at the market, we assumed 14 days when cost were per day.

Cash revenus

We calculated the income obtained from the sell of both 50kg bags and 90 kg bags at the average, low and high prices as reported by each producer based on their own experience. Here we present the calculation of income per producer for the mean price provided in the survey:

$$Income_{mean} = (Nb_{50kgbags} * MeanPrice_{50kgbags}) + (Nb_{90kgbags} * MeanPrice_{90kgbags})$$

Net cash gains

Other scenarios were evaluated based on the low and high price received by the producer.

$$NetGain = Income_{mean} - Costs_{total}$$