The connection between forest degradation and urban energy demand in Sub-Saharan Africa: A characterization based on high-resolution remote sensing data.

Sedano, F. [1], Lisboa, S. N. [2], Sahajpal R. [1], Duncanson L. [1], Ribeiro, N. [2], Sitoe, A. [2], Hurtt G. [1], Tucker C. J[3].

[1]Department of Geographical Sciences, University of Maryland, US.

[2]Department of Forest Engineering, Faculty of Agronomy and Forest Engineering, UEM, Mozambique

[3]NASA - Goddard Space Flight Center, US.

Keywords: *forest degradation, charcoal production, urban energy demand, high-resolution remote sensing, sub-Saharan Africa*

Research Highlights:

- *Annual forest degradation from charcoal production in study area reached 103 km^2 on average*
- *Charcoal production degraded 55.5 % of the mopane woodlands in 7 years*
- *Kiln densities in the study area reached up to 2 kilns-ha and AGB removals of 90.7 Mg/ha*
- *Urban energy demand linked to the degradation of 175 km^2 of woodlands annually*
- *Current charcoal production patterns are not sustainable*

Abstract

Charcoal is a key energy source for urban households in sub-Saharan Africa and charcoal production is the main cause of forest degradation across the region. We used multitemporal high-resolution remote sensing optical imagery to quantify the extent and intensity of forest degradation associated with charcoal production and its impact on forest carbon stocks for the main supplying area of an African capital. This analysis documents the advance of forest degradation and quantifies its aboveground biomass removals over a 7-year period, registering that, between 2013 and 2016, the average annual area under charcoal production was 103 km^2 and the annual aboveground biomass removals reached 1,081,000 (SD = 2,461) Mg. Kiln densities in the study area rose to 2 kilns-ha, with an average of 90.7 Mg/ha of extracted aboveground biomass. Charcoal production was responsible for the degradation of 55.5 % of the mopane woodlands in the study area between 2013 and 2019. We estimated post-disturbance recovery times using an ecosystem model calibrated for the study area. The simulations showed that recovery times could require up to 150 years for current aboveground biomass extraction rates. The results of the remote sensing analysis and the simulations of the ecosystem model corroborate the unsustainability of the present patterns of charcoal production. The detailed characterization of the spatial and temporal patterns of charcoal production was combined with household survey information to quantify the impact of the urban energy demand of the Maputo urban area on forest carbon stocks. The analysis shows that Maputo charcoal demand was responsible for the annual degradation of up to 175.3 km^2 and that the contribution of the study area to this demand fluctuated between 75 and 33 % over the study period. The extent, advance pace and distance from urban centers documented in this study support the idea that forest degradation from charcoal production cannot merely be considered a peri-urban process. The intensity of the AGB removals and its contribution to forest carbon stocks changes is significant at the national and regional levels.

1. Introduction

Africa is experiencing a rapid urbanization process (Grant, 2016). While only 30 % of the African population lived in urban centers in 2000, forecasts indicate that this figure will reach 60 % in 2050 (UN-Habitat, 2014). This urbanization process is expected to have major implications for the natural environments within the growing sphere of influence of the cities (Grim et al., 2008), and it could potentially reshape rural landscapes (Güneralp et al., 2020). The connection between urban demand for food and fiber and environmental degradation has been extensively documented (DeFries et al., 2010; Satterthwaite et al., 2010; Seto & Ramankutty, 2016; Boudet et al., 2020). Yet, in sub-Saharan Africa (SSA) the link between urban energy demand and forest carbon stock changes is particularly relevant (Arnold et al., 2006; Clancy, 2008). Traditional biomass accounts for almost half of the energy consumption in Africa, and charcoal is the main cooking energy source for African urban centers in 21 countries of SSA (ICF, 2012; IEA, 2019). Close to 80 % of households use charcoal as part of their cooking energy mix across SSA (Zulu and Richardson, 2013). While access to alternative energy sources may increase with income, charcoal is expected to remain a dominant source of energy for African urban households in the coming decades and the overall charcoal consumption is expected to increase by 2040 (Girard, 2002; Zulu, 2010; IEA, 2014; Dam, 2017). Yet, despite its relevance, the lack of consistent and reliable information about the charcoal sector results in a poor understanding of the magnitude of the problem and its potential negative impacts that hinders the subsequent development of effective specific interventions (Broadhead et al., 2001; Kissinger et al., 2003; Chidumayo & Gumbo, 2013, Mwampamba et al., 2013). Narratives about the impact of charcoal production on forest resources have evolved over the last decades, from the crisis narratives in the 1970’s (Eckholm, 1975; Anderson & Fishwick, 1984) to more forbearing assessments (Leach and Mearns 1988; Ribot 1999; Hosier, 1993; Kissinger et al., 2003; Arnold et al., 2003). Yet, most of these narratives have often been rooted in partial information, over-generalizations and a misrepresentation of the charcoal sector (Mwampamba et al., 2013).

Hosonuma et al., (2012) identified charcoal production as the main cause of forest degradation in SSA. Most of this charcoal is produced from natural forests and woodlands in a process that, while initially highly selective, becomes more indiscriminate in successive waves (Dam, 2017; Chidumayo, 2019; Silva et al., 2019). Current efforts highlight the need for data-driven assessments to understand and quantify the contribution of charcoal production to forest degradation and its impact on forest resources (FAO, 2003; Mwampamba t al., 2007; Chidumayo 2019).

Forest degradation can be defined as the reduction of the capacity of a forest to provide goods and services, including biomass, carbon sequestration, water regulation, soil protection, and biodiversity conservation (FAO, 2011). Forest degradation is a main factor behind uncertainties in global emissions from forest loss (Bullock et al., 2018). The impact of fire-driven forest degradation to carbon emissions is clearly recognized and, while substantial uncertainties remain, fire-driven forest degradation is currently estimated for as part of global fire emissions (van der Werf et al., 2017; Lasslop et al., 2019). Monitor and quantify non-fire-driven forest degradation has proved more challenging, as it commonly requires multiple AGB measurements over time. Most countries in SSA lack historical NFI data and permanent plots to provide suitable carbon emission estimates associated with forest degradation processes (Herold et al., 2011). Monitoring forest degradation from charcoal production with Earth observation data also remains a challenge (Herold et al., 2012; Goetz et al., 2015, Gao et al., 2020), but recent studies have demonstrated the feasibility of approaches based on multitemporal medium resolution Earth Observation data (Sedano et al., 2020a; Sedano et al., 2020b). Yet, charcoal production results in small-scale disturbances. Its impact on the spectral signal can be both subtle, because it implies a partial removal of vegetation cover, and short-lived, because regrowth soon restores a continuous vegetation cover in the disturbed site. As a consequence, detection with medium resolution sensors is not always feasible. In the last few years, some studies have explored the use of high-resolution imagery to indirectly map charcoal production (Bolognesi et al., 2015; Dons et al., 2015, Sedano et al., 2016). Following this line of research, this study takes advantage of multitemporal dataset of high and very high-resolution imagery to characterize the spatial and temporal dynamics of charcoal production in a prominent charcoal production area of southern Mozambique. The reliance on charcoal of Maputo started during the civil war (1975 - 1992) when urban population rapidly expanded (Cities Alliance, 2017). As forested areas in the vicinity of the city were depleted, charcoal production gradually moved further away: within 50-60 km in the 1980's, between 60 and 100 km in the 1990's, and 150-200 km during the earlier 2000´s (CHAPOSA, 2002). Since 2010, the district of Mabalane, 350 km north of Maputo, has been the main charcoal supplying area (Luz et al., 2015). To our knowledge, this case study represents the most detailed assessment of forest degradation from charcoal production to the date. We combine this information with survey data on urban charcoal consumption to establish a direct link between energy demand of a main urban center in the region and a supplying woodland area, in an attempt to quantify the impact of the urban energy demand from SSA cities on forest carbon stocks.

2. Study area

The study area corresponds to the administrative subdivision of Combomune, in the district of Mabalane, province of Gaza, southern Mozambique (Figure 1). Combomune (Lat S 23.1; Long E 33.0) covers 5,163 km^2 and it is located 350 km North from Maputo, the country's capital.

The area is mostly flat, with an altitudinal gradient from 50 to 170 m and loamy sand soils (Woollen et al., 2016). The average annual temperature is 24 C and annual precipitation is 530 mm, with a clearly defined dry season from May to September. Woodland ecosystems in the study area dominated by formations of mopane (*Colophospermum mopane* (Benth.) J. Léonard), combretum (*Combretum* sp.) and mecrusse (*Androstachys johnsonii* Prain), in which these trees form quasi-monospecific stands. Because of its relative abundance, high wood density (1,020 – 1,140 kg/m^3) (Carsan et al., 2012) and relatively straight logs, mopane trees are the preferred species for the production of high-quality charcoal. Hence, most of the charcoal production takes in mopane woodlands that cover around 735.3 km^2 (14.2 % of the total area) of the study area. As mopane trees become rare, some suboptimal charcoal tree species (e.g., *Combretum* sp.) are more frequently used by charcoal producers (Woollen et al., 2016).

Since the year 2008 the district of Mabalane has produced a large proportion of the charcoal consumed in the city of Maputo (Luz et al., 2015; Baumert et al., 2016), with production gradually moving northwards as undisturbed mopane woodlands became scarce in the southern sections of the district. In 2013 the largest share of the production was already concentrated in Combomune. Charcoal production in Combomune supplies the Maputo urban area, with a population of 2 million people (Instituto Nacional de Estatistica – INE, 2017). Up to 87 % of households in Maputo urban area use charcoal, and between 44 and 69 % of them use it as their primary cooking energy source (Atanassov et al., 2012; ICF, 2012).

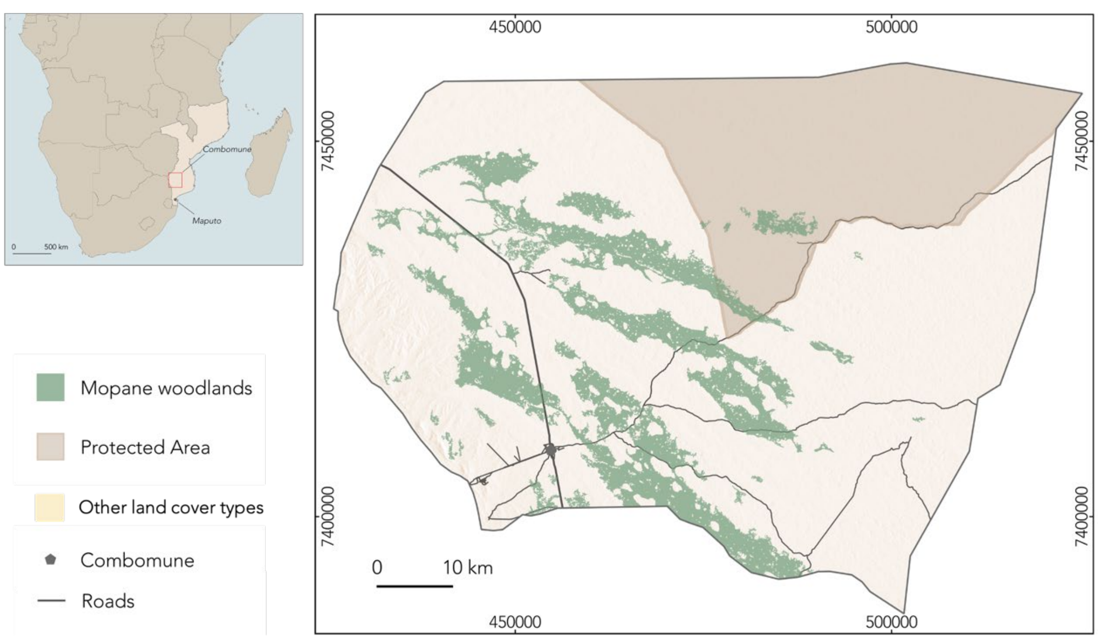

Figure 1. Red rectangle in upper left panel indicates the location of the study are in southern Mozambique. Large panel shows the Combomune study area and the distribution of mopane woodlands where charcoal production is concentrated.

3. Data

We compiled a multisensor dataset of high-resolution imagery to provide annual coverage of the mopane woodlands of the study area for each year between 2013 and 2019 (Table 1). The dataset included 153 multispectral images with cloud coverage below 5 % from WorldView2, Rapid Eye and PlanetScope platforms obtained from the Maxar and Planet archives respectively. Images from the Maxar archive were obtained from the NASA National Geospatial Intelligence Agency (NGA) archive (Neigh et al 2013) and images from the Planet archive were obtained through an Education and Research Program license (Planet, 2017). The images for each year provided a complete coverage for years 2013, 2016, 2017, 2018 and 2019 (Figure 2). Multispectral images for 2014 only covered 77 % of the mopane woodlands and were complemented with four WorldView1 panchromatic very high-resolution images (0.5 m) covering an additional 21 % of the mopane woodlands. The images in this dataset were used to map kiln scars on an annual basis. Rainy season imagery was only used if dry season images were not available. When images from several sensors were available, the highest spatial resolution images were always preferred. In addition, we compiled a dataset of fourteen cloud-free WorldView1 panchromatic very high-resolution images (0.5 m) from the 2014 dry season (December). The images in this dataset covered 50 % of the study area and it was used to estimate kiln scar dimensions at a sample of locations within the charcoal production areas.

ID	Reference Year	Imagery years	Archive	Sensors	Spatial Res.(m)	Number of Images	Acquisition Window	Mopane woodlands coverage (%)
1	2013	2013	Maxar	WorldView2	2	20	June 13, July 10	100
2	2014	2014	Maxar	WorldView2	2	11	December 3	77
2b	2014	2015	Maxar	WorldView1	0.5	4	February 18	21
3	2015	2015	Planet	Rapid Eye	5	13	September 15	100
4	2016	2016	Maxar	WorldView2	2	18	June 16	100
5	2017	2017	Planet	PlanetScope	3	39	November 21	100
6	2018	2018	Planet	PlanetScope	3	32	November 17	100
7	2019	2019	Planet	PlanetScope	3	21	October 7	100

Table 1. Description of imagery used in the study.

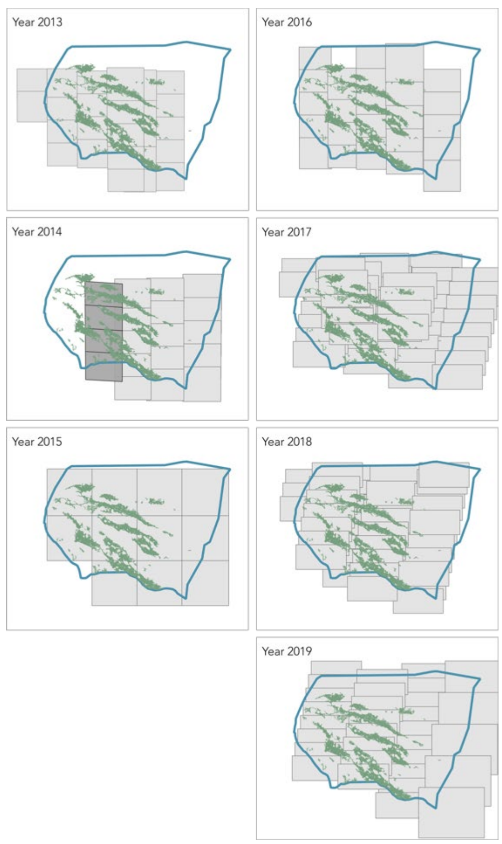

Figure 2. High-resolution imagery coverage. Annual coverage of high-resolution imagery for the study area. Imagery corresponds to DigitalGlobe archive (years 2013-2016) and Planet archive (2017-2019). Dark grey 2014 footprints correspond to very high-resolution panchromatic WorldView1 images.

4. Methods

4.1 Forest degradation extent

We applied a region growing segmentation approach (RG) to map the spatial distribution of charcoal kiln scars in the study area with a multitemporal dataset of high-resolution imagery at seven annual epochs between 2013 and 2019 (Figure 3). The RG clustered spatially contiguous regions based on discontinuities of intensity levels between kiln scars and neighboring pixels. The RG approach also incorporated size and shape criteria established from fieldwork observations to simplify the segmentation problem and improve its robustness (see supplementary materials). In this sense, with the inclusion of a priori knowledge about the charcoal production process, this approach combines elements from both knowledge-based and object-based image analysis methods (Cheng & Han, 2016).

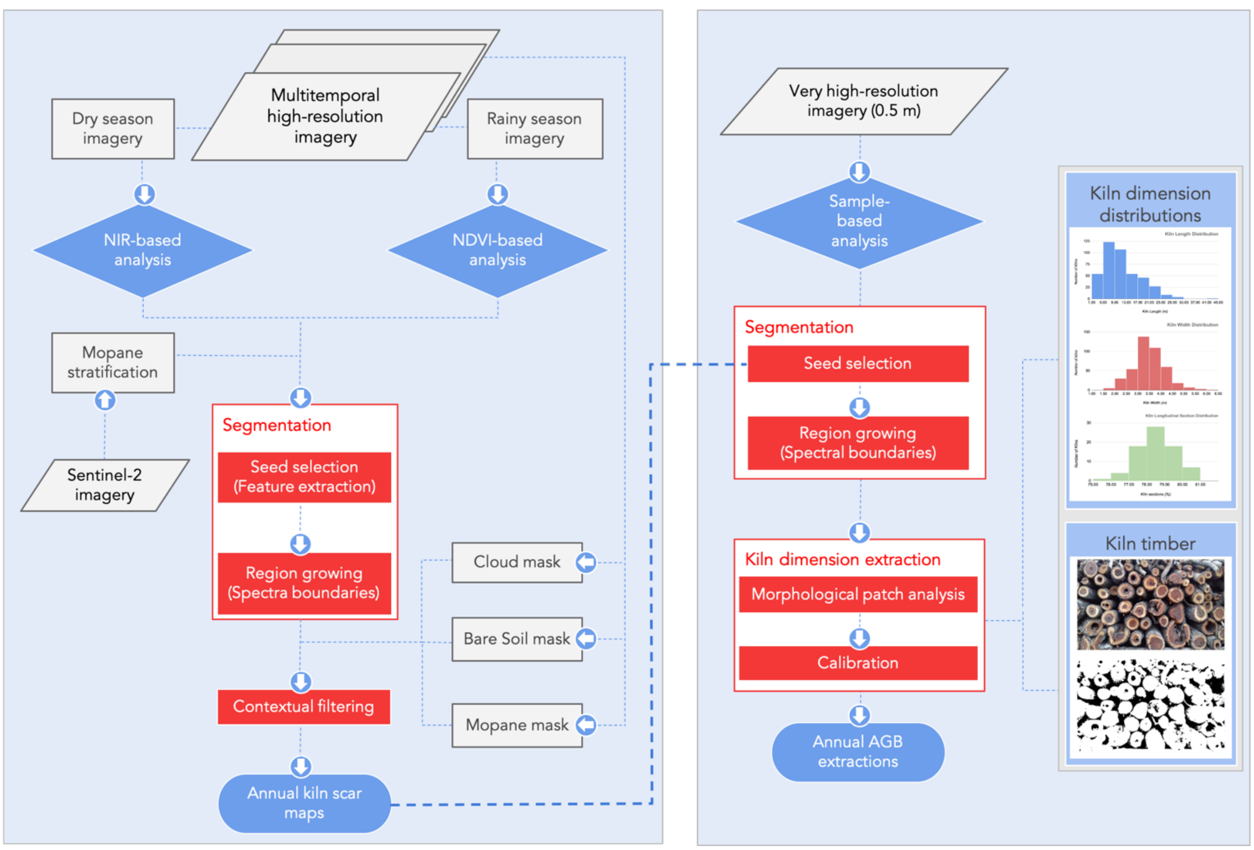

Figure 3. Flowchart of methodology for kiln scar mapping (left-side box) and kiln dimension extraction (right-side box).

The spectral contrast between kiln scars and surrounding areas is the highest for late dry season conditions (July - December), and gradually declines with the offset of the rains, as vegetation covers the ground. Therefore, when available, late dry season images were used for the analysis. RG was applied on a single band basis, with NIR band as a default option. As an alternative, NDVI images were used when only rainy season (January - June) images were available. The implementation of this region-based segmentation process retrieved kiln scar maps in the study area for each year between 2013 and 2019 (Figure 4). The reported number of kilns per year was proportionally adjusted to account for the different length of periods between imagery epochs. A visual identification of the kiln scars in the high-resolution images was carried out to validate the accuracy of the kiln scars maps (Congalton & Green, 2009). The validation took place in twenty blocks of 100 ha randomly selected for each year (total = 140 blocks) within the mopane woodlands of the study area. Commission and omission errors and successful detection rate (%) were reported for each year and the whole study period.

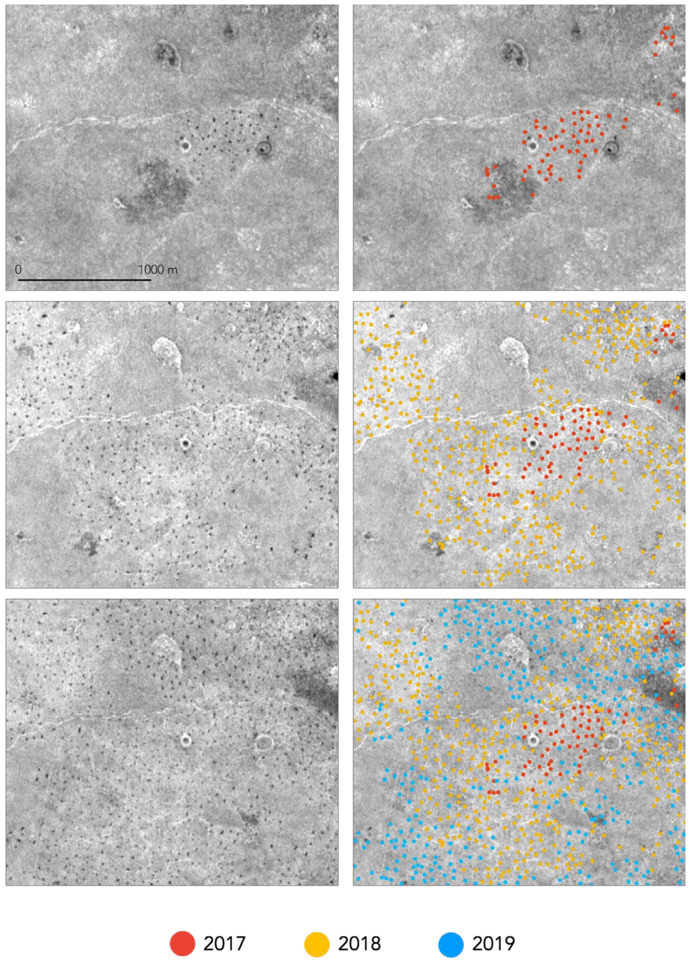

Figure 4. Subset of Planet images (3 m) for three consecutive years (2017-2019) in charcoal production area: NIR bands (Left side panels); and detected kiln scars (Right side panels).

The average kiln density was estimated from mapped kiln scars at four randomly selected sites in the mopane woodlands of the study area. These sites covered an overall area of 112 km^2 and included 18,929 kilns in the calculation. The progression of disturbed mopane woodlands during the study period was estimated at each imagery epoch based on the presence of kiln scars within 1 km^2 square cells of a grid covering the study area. Grid-cells were labeled as disturbed if more than ten kilns were found within the cell. Only grid cells with more than 20 % of its area covered by mopane woodlands were considered in the analysis.

4.2 Aboveground Biomass removals

A second region growing routine was implemented to extract kiln scar dimensions from very high-resolution (0.5 m) panchromatic WorldView1 images from the year 2014. This analysis was carried out in six sample locations with charcoal production activities. The total area of these locations covered 154 km^2 and contained 10,823 kiln scars. This region growing routine used the kiln scars detected during kiln scar mapping as seed pixels and expand or contract them based on the spectral similarity between seed and neighboring pixels, size, and shape criteria. The two main axes of each region were calculated as an approximation to kiln scar dimensions (length and width) (Figure 5). Next, we applied a histogram matching to calibrate image-based kiln scar dimensions to kiln dimensions measured in the field (see supplementary materials).

Subsequently, annual AGB removals from charcoal production were calculated as the sum of the wood biomass extracted to build all the kilns mapped with the high-resolution images of the study area. The wood biomass used for each kiln was estimated as a product of the kiln dimensions, kiln wood volume proportion, AGB debris, and mopane wood density, drawing Monte Carlo simulations from the statistical distributions of these parameters (see supplementary materials). Successively AGB extractions per hectare were estimated as the product of the average kiln density and kiln wood.

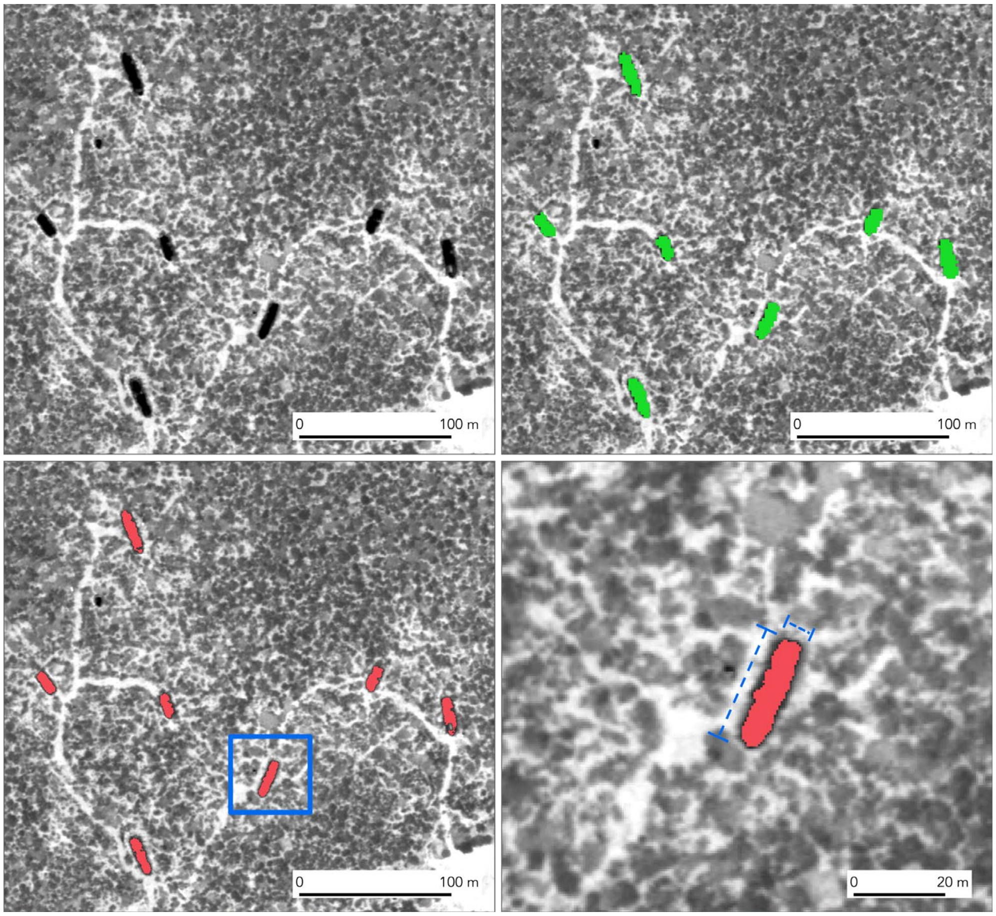

Figure 5. Example of kiln dimension extraction sequence. Top-left: subset of 0.5 m panchromatic WorldView1 image; Top-right: kiln scars detected from high-resolution imagery used as initial seeds for kiln dimension extraction; Bottom-left: kiln scars mapped in 0.5 m panchromatic WorldView1 image with region growing segmentation approach; Bottom-right: detailed view of kiln scar with length and width dimensions extracted from main two axes.

We used the Ecosystem Demography (ED) model (Moorcroft et al., 2001, Hurtt et al., 2002) to simulate potential AGB and AGB regrowth after charcoal production disturbance in the ecological conditions of the study area (see supplementary materials).

The annual charcoal demand of the Maputo urban area was estimated from population figures (INE) and household-level charcoal consumption estimates. Household charcoal consumption was estimated as a weighted average of daily charcoal consumptions for households with different energy mixes obtained from Atanassov et al. (2012). Five-member households were assumed. Charcoal conversion efficiency (25 %) was obtained from previous studies in the region (CHAPOSA, 2002).

5. Results

We mapped 110,058 kiln scars in the study area between 2013 and 2019, with a peak between 2013 and 2016 and a gradual decline in successive years (Figure 6; Figure 7). The validation of the results showed the robustness of the mapping approach, with 99.3 % of the kiln scars were correctly mapped and the overall commission and omission errors were 0.7 and 3.0 %, respectively. The accuracy metrics were consistent across all sensors and years of analysis (Table 2).

Year	Omission Error (%)	Commission Error (%)	Overall Accuracy (%)
2013	2.51	1.85	98.15
2014	4.06	0	100
2015	1.76	1.52	98.48
2016	2.71	1.22	98.78
2017	4.32	0.30	99.70
2018	2.74	0.71	99.29
2019	1.77	0	100

Table 2. Accuracy metrics for kiln scar detection in high-resolution imagery.

AGB removals from mapped kilns for the 7-year period accounted for 5,129,900 Mg (SD = 9,232) with 1,081,000 (SD = 2,461) Mg extracted annually during the peak 2013 - 2016 period. The inclusion of adjacent kilns, not mapped in this study, could represent a 3.1 % increase in AGB removals.

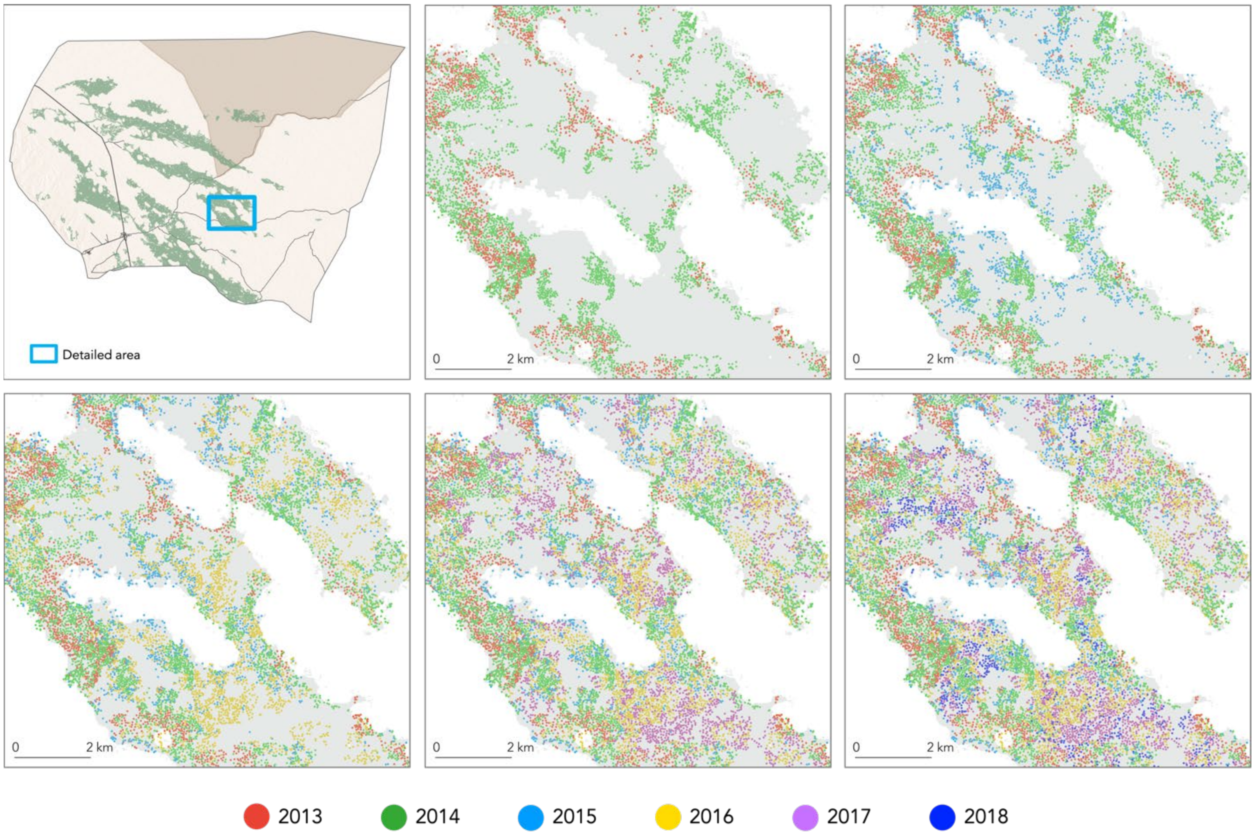

Figure 6. Progression of kiln scars in the mopane woodlands of the study area for a 6-year sequence (2013-2018).

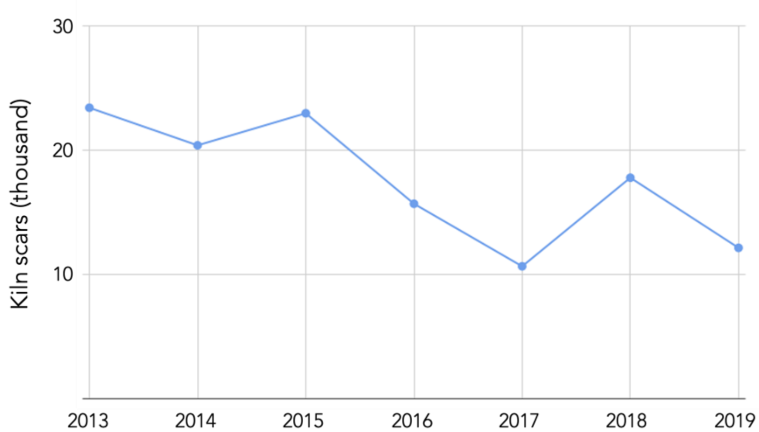

Figure 7. Annual number of kiln scars for every year adjusted to account for the different length of periods between imagery epochs.

Charcoal production in the study area is a fast-moving process. The grid-level analysis showed that undisturbed mopane woodlands (e.g., woodlands without evidence of charcoal production) decreased from 65% in 2013 to 9.5 % in 2019. The spatio-temporal progression of the kiln scar locations follows a centrifugal pattern of forest degradation, and over the years, kilns are found further away from primary and secondary roads, progressively moving into more remote woodlands. The progression of kiln locations also reveals a gradual intensification of charcoal production activities in fewer clusters of production that concentrate on an increasing number of kilns (Figure 8).

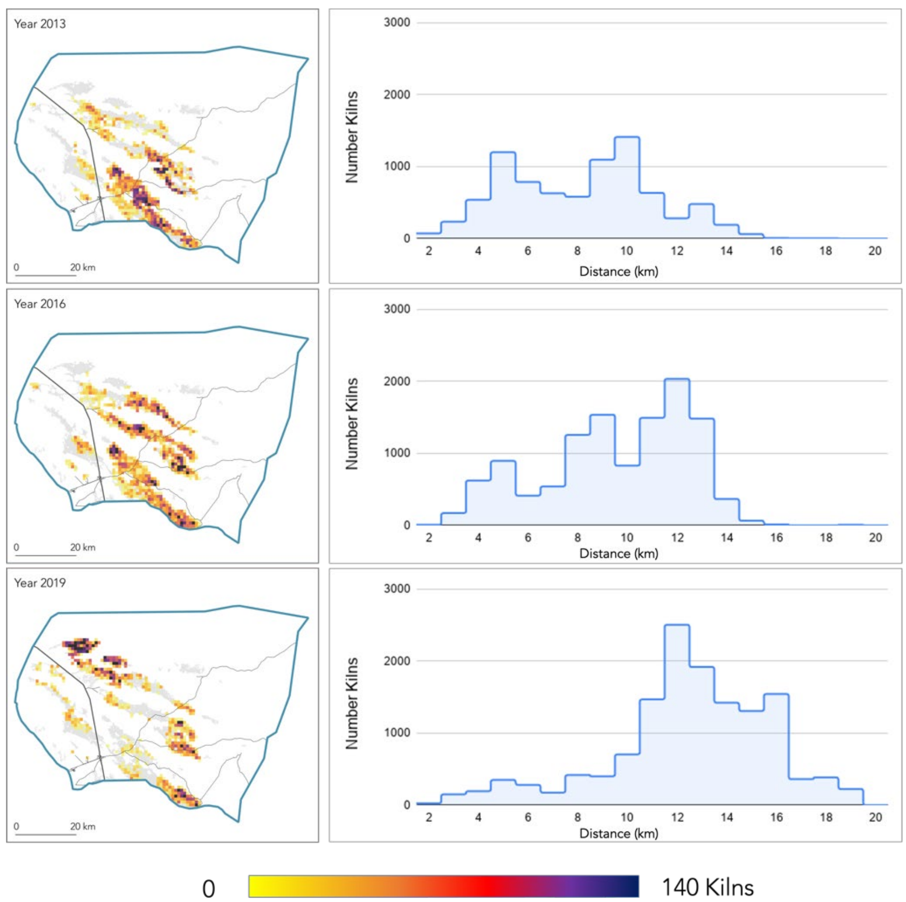

Figure 8. Grid-level (1 km) kiln density maps for a sequence of three years (2013, 2016, 2019) in the study area (Left column); and corresponding distribution of kiln frequencies with distance from the main village in the study area (Right column).

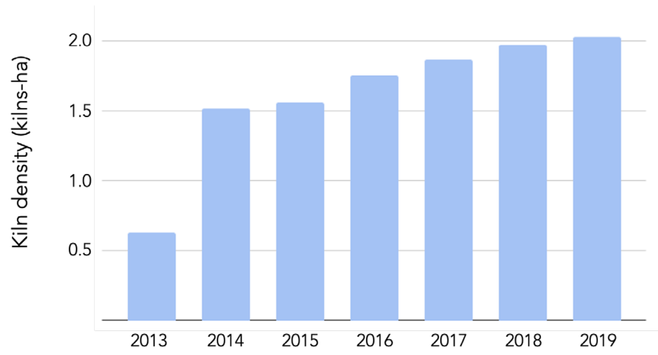

Figure 9. Evolution of the average kiln density at site level.

Woodland stands commonly support charcoal production for a number of years with a gradual increase of AGB removals at site level is observed (Figure 9). While charcoal making starts slowly, with kiln densities of 0.6 after the first year, production intensity quickly accelerates to surpass densities of 1 kiln per ha in successive years. The final season of production in a site, kiln density can reach two kilns per ha, with kilns around 79.6 m apart and average AGB removals of 90.7 Mg/ha (SD= 40.10). Ecosystem model forecasts indicate that, in the absence of active forest management, these AGB extraction patterns would require up to 150 years to recover to pre-disturbance AGB levels (Figure 10).

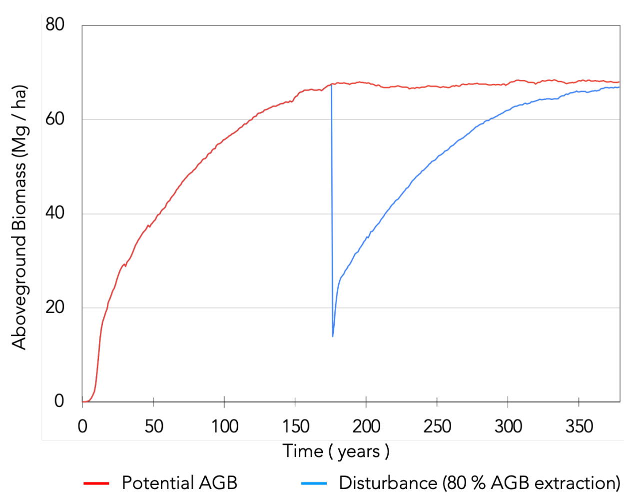

Figure 10. ED ecosystem model projection of aboveground biomass recovery after charcoal production disturbance for ecological conditions in the study area.

The annual AGB required to meet the charcoal demand of the Maputo urban area was estimated at 1.61 million Mg on average. Assuming the AGB extraction patterns identified in the analysis of the high-resolution imagery and current population growth projections, this amount of AGB would require 35,456 kilns and cover an average area of 175.3 km^2 of woodlands annually. Based on the kiln scars detected during the study period, the contribution of the study area to the charcoal demand of Maputo gradually decreased from up to 75 % in 2013 to 31 % in 2019.

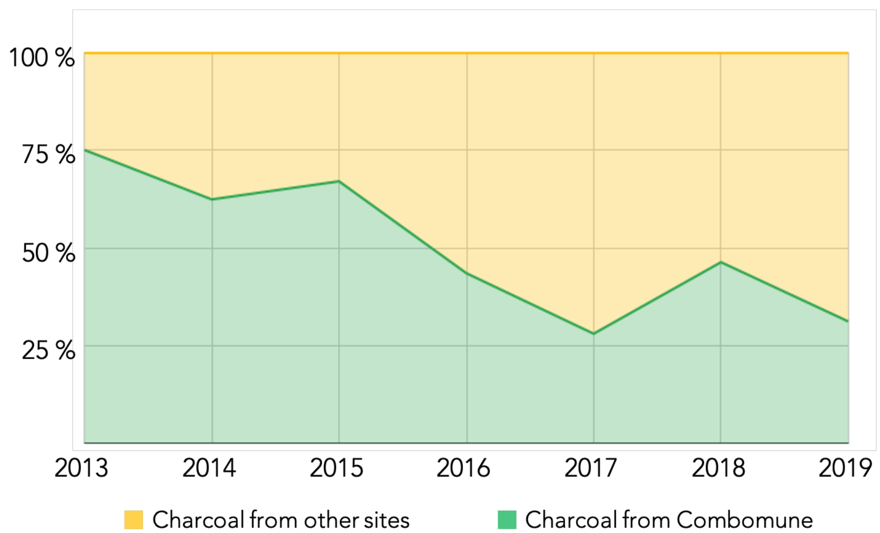

Figure 11. Evolution of the contribution of the charcoal produced in the study area to the overall Maputo urban area charcoal consumption.

6. Discussion

We have applied an indirect approach to map forest degradation from charcoal production in tropical woodlands of southern Africa from a multitemporal and multisensor dataset of high and very high-resolution imagery. This approach detected kiln scars and estimated kiln dimensions as a proxy to quantify forest degradation extent and its AGB removals respectively. The results for the main production area in southern Mozambique offer a detailed characterization of spatial and temporal dynamics, the magnitude and the intensity of this forest degradation process. They also significantly improve the precision of previous remote sensing assessments based on medium resolution imagery (Sedano et al., 2020b). Because of its larger area coverage and the length of the period of study, this work also represents an advance from previous high-resolution efforts. The proposed mapping approach integrated a priori knowledge of the charcoal production at various stages of the mapping process, including image selection, delimitation of the geographical scope of the analysis, and design and calibration of the mapping method. This knowledge contributed to reduce the complexity of the segmentation, minimizing potential omission and commission errors and thus improving the robustness of the kiln scar mapping. The high accuracy of the results stresses the importance of a clear understanding of the main characteristics of the charcoal production process to simplify the mapping routine and reduce its uncertainties. This study represents a proof of concept of the capabilities of high-resolution Earth observation data to monitor and quantify the impact of charcoal production-related forest degradation in SSA. With increasing access to high-resolution imagery and decreasing computing power restrictions, monitoring systems can now reach a level of maturity that allows operation implementation. The development of such monitoring systems will enable the explicit inclusion of forest degradation driven by charcoal production in REDD+ MRV systems in a sub-Saharan Africa context in compliance with international guidelines and recommendations.

The number of kilns mapped in the multitemporal high-resolution imagery for seven years fluctuated over time, with a peak during between 2013 and 2016 and a gradual decrease in successive years. This decrease reflects the gradual decline of undisturbed woodlands in the study area following a centrifugal process already documented in medium resolution assessments for this study area (Sedano et al., 2020a) and in other locations in eastern Africa (Ahrends et at., 2010). Forest degradation advance was accompanied by a progressive intensification of AGB extraction at site level, to reach kiln densities of 2 kilns/ha and AGB removals of 90.7 Mg/ha on average (SD= 40.10) in some locations. The large uncertainties in site extractions, characterized by the Monte Carlo simulations, are due to the large variation in kiln sizes across the study area. These extraction figures are in agreement with field measurements in the study area (Sedano et al., 2020a), and represent further evidence of the unsustainability of the current charcoal production regime in the supplying areas of Maputo, also supported by the long AGB recovery times in ecosystem model simulations. Similar conclusions had been also reported by Drigo et al. (2008) using a supply-demand approach. Although AGB recovery times will change from site to site depending on the specific environmental conditions, similar unsustainable extraction patterns have been reported elsewhere in the Miombo region and point towards the regional prevalence of the problem (Mwampamba et al., 2007; Chidumayo 2019).

Mabalane, approximately 350 km north of Maputo, has been its main charcoal supplying district since 2010 (Luz et al., 2015) and, since 2013, most of this activity has been concentrated in Combomune (Sedano et al., 2020b). While charcoal arriving in Maputo comes from several production areas in the country (Atanassov et al., 2012), the charcoal produced in Combomune is exclusively consumed in the city of Maputo. This unidirectional transfer provides a platform to understand the increasing impact of urban energy demand in forest carbon stock changes. Charcoal production in Combomune during the year of highest production (2013 – 2016) covered an annual average of 103 km^2 and was responsible for the extraction of 1,083,500 Mg of AGB (SD = 2,429). These figures offer a lower envelope estimate of the impact of Maputo charcoal demand on forest resources. The combination of information from household surveys (Atanassov et al., 2012) and charcoal production patterns extracted from high-resolution EO data indicate that this amount would not be enough to satisfy the annual charcoal demand of Maputo (Figure 11). An urban center as Maputo would require on average, the use of an additional 41 % area of woodlands to cover its annual charcoal needs. This footprint, both in extent and intensity, together with the fact that production sites are located more than 350 km away, supports the narrative that forest degradation from charcoal production cannot any longer be considered a localized process restricted to peri-urban areas.

The quantification of the impact of Maputo charcoal consumption on forest resources offers a valuable reference point for other urban centers across the Miombo region and elsewhere in sub-Saharan Africa. Charcoal is the main urban cooking energy source in seven urban areas with more than one million people in the Miombo region and nineteen other cities within the region are expected to reach this population in the next 20 years (UN, 2019). Across the continent, charcoal use is also the main energy source of large cities of West Africa and East Africa. While the magnitude, intensity of forest degradation driven by charcoal production will be different for each urban area depending on its intrinsic circumstances (e.g., existing forest resources, policy interventions, law enforcement, etc.), it is reasonable to expect that, under current scenarios, each of these urban centers will develop their own charcoal supplying areas. Renewable energies and recently discovered natural gas deposits have the potential to lead Africa's energy transition from solid biomass and boost its overall energy consumption growth. Yet, this transition will require a considerable effort. Current efforts to ensure access to electricity, reliable electricity supply and clean cooking barely outpace population growth (EIA, 2019). Thus, charcoal is expected to remain a prominent energy source in urban Africa over the next decades and the footprint of charcoal production, already noticeable at regional level, is likely to become more pronounced.

7. Conclusion

We have characterized and quantified the impact of charcoal production on forest degradation for the main supplying area for major African capital. We mapped the extent and intensity of forest degradation from charcoal production using a multitemporal dataset of high and very high-resolution imagery from various platforms. Despite its relevance in SSA, the contribution of charcoal production to changes in forest stocks is currently not explicitly quantified and reported. This work represents a proof of concept of the potential for operational monitoring of the main cause of forest degradation in the region. Our results expose with high spatial detail a fast-moving and intense forest degradation process and underscore its long-term impact on forest carbon stocks. These results challenge the narratives that downplay the role of charcoal production on forest cover changes and describe it as a localized and peri-urban problem. The univocal link between the supplying area and the urban center in this study allowed a first quantification of the footprint of the urban energy demand on forest carbon stocks. This quantification provides a valuable initial reference point to estimate and assess the importance of this forest degradation process at regional level. As large urban centers continue growing and the number of large cities, charcoal supplying areas are expected to become larger, more numerous and move further away from cities.

8. Acknowledgements

We would like to thank the two anonymous reviewers for their suggestions and comments. This study is part of the ‘Forest degradation caused by charcoal production: characterization, quantification and forecasting to improve carbon monitoring systems in southern Africa’ project and it is supported by from NASA Carbon Monitoring System (16-CMS16-0041). DigitalGlobe imagery were used under the National Geospatial- Intelligence Agency’s (NGA) NextView License Agreement. (© 2016 DigitalGlobe, Inc. Licensed under NextView). PlanetScope imagery was used under a Planet Education and Research Program license.

9. Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

10. References

Ahrends A, Burgess N D, Milledge S A H, Bulling M T, Fisher B, Smart J C R, Clarke G P, Mhoro B E and Lewis S L 2010 Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city *Proc. Natl. Acad. Sci.* **107** 14556–61

Anderson D, Fishwick R 1984 Fuelwood consumption and deforestation in African countries 1

Arnold J E M, Köhlin G and Persson R 2006 Woodfuels, livelihoods, and policy interventions: Changing Perspectives *World Dev.* **34** 596–611

Arnold M, Köhlin G, Persson R and Shepherd G 2003 *CIFOR Occasional Paper No. 39 Fuelwood Revisited: What Has Changed in the Last Decade?*

Atanassov -Andrade B, Falcão E-M, Fernandes A and Mahumane G 2012 *Capacity Building in Energy Planning and Management EuropeAid/127640/SER/MZ* Mozambique Urban Biomass Energy Analysis 2012. Maputo-Matola-Beira-Nampula. *Mozambique Ministry of Energ. Maput*

Baumert S, Luz A C, Fisher J, Vollmer F, Ryan C M, Patenaude G, Zorrilla-Miras P, Artur L, Nhantumbo I and Macqueen D 2016 Charcoal supply chains from Mabalane to Maputo: Who benefits? *Energy Sustain. Dev.* **33** 129–38

Bolognesi M, Vrieling A, Rembold F and Gadain H 2015 Rapid mapping and impact estimation of illegal charcoal production in southern Somalia based on WorldView-1 imagery *Energy Sustain. Dev.* **25** 40–9

Boudet F, MacDonald G K, Robinson B E and Samberg L H 2020 Rural-urban connectivity and agricultural land management across the Global South *Glob. Environ. Chang.* **60** 101982

Broadhead J, Bahdon J and Whiteman, A 2001 Woodfuel consumption modelling and results. Annex 2 in Past trends and future prospects for the utilization of wood for energy, Working Paper No: GFPOS/WP/ 05, Global Forest Products Outlook Study, FAO, Rome.

Bullock E L, Woodcock C E and Olofsson P 2020 Monitoring tropical forest degradation using spectral unmixing and Landsat time series analysis *Remote Sens. Environ.* **238** 110968

Carsan S, Orwa C, Harwood C, Kindt R, Stroebel A, Neufeldt H, and Jamnadass R 2012 African Wood Density Database. World Agroforestry Centre, Nairobi.

CHAPOSA 2002 Charcoal Potential in Southern Africa (CHAPOSA) *Stock. Environ. Inst.* 1–88

Cheng G and Han J 2016 A survey on object detection in optical remote sensing images *ISPRS J. Photogramm. Remote Sens.* **117** 11–28

Chidumayo E N and Gumbo D J 2013 The environmental impacts of charcoal production in tropical ecosystems of the world: A synthesis *Energy Sustain. Dev.* **17** 86–94

Chidumayo E N 2019 Is charcoal production in Brachystegia-Julbernardia woodlands of Zambia sustainable? *Biomass and Bioenergy* **125** 1–7

Cities Alliance 2017 Urbanization in Mozambique Assessing Actors, Processes, and Impacts of Urban Growth. Research Monograph. Rue Royale 94, 1000 Brussels, Belgium.

Clancy J S 2008 Urban ecological footprints in Africa *Afr. J. Ecol.* **46** 463–70

Congalton R G and Green K 2019 *Assessing the Accuracy of Remotely Sensed Data* (CRC Press)

Dam J van 2017 *The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods* (Rome)

Defries R S, Rudel T, Uriarte M and Hansen M 2010 Deforestation driven by urban population growth and agricultural trade in the twenty-first century *Nat. Geosci.* **3** 178–81

Dons K, Smith-Hall C, Meilby H and Fensholt R 2015 Operationalizing measurement of forest degradation: Identification and quantification of charcoal production in tropical dry forests using very high resolution satellite imagery *Int. J. Appl. Earth Obs. Geoinf.* **39** 18–27

Eckholm E P 1975 *The other energy crisis, firewood* (Washington: [Worldwatch Institute])

FAO 2011 *Assessing forest degradation Towards the development of globally applicable guidelines. Working Paper 177* (Rome)

Gao Y, Skutsch M, Paneque-Gálvez J and Ghilardi A 2020 Remote sensing of forest degradation: a review *Environ. Res. Lett.* **15**

Girard P 2002 Charcoal production and use in Africa: What future? *Unasylva* **53** 30–4

Goetz S J, Hansen M, Houghton R A, Walker W, Laporte N and Busch J 2015 Measurement and monitoring needs, capabilities and potential for addressing reduced emissions from deforestation and forest degradation under REDD+ Related content *Environ. Res. Lett.* **10**

Grant R 2016 Africa: Geographies of Change - Edited by Richard Grant, Oxford: Oxford University Press. 2015. 356 pp. ISBN 978-0-19-992056-3 (paperback). *Growth Change* **47** 130–1

Grimm N B, Faeth S H, Golubiewski N E, Redman C L, Wu J, Bai X and Briggs J M 2008 Global change and the ecology of cities *Science (80-.).* **319** 756–60

Güneralp B, Lwasa S, Masundire H, Parnell S and Seto K C 2018 Urbanization in Africa: Challenges and opportunities for conservation *Environ. Res. Lett.* **13**

Herold M, Román-Cuesta R M, Mollicone D, Hirata Y, Van Laake P, Asner G P, Souza C, Skutsch M, Avitabile V and MacDicken K 2011 Options for monitoring and estimating historical carbon emissions from forest degradation in the context of REDD+ *Carbon Balance Manag.* **6** 1–7

Herold M, Román-Cuesta R M, Heymell V, Hirata Y, Van Laake P, Asner G P, Souza C, Avitabile V, MacDicken K 2012 A review of methods to measure and monitor historical carbon emissions from forest degradation. Unasylva 238, 62, 2011/2.

Hosier R H, Mwandosya M J and Luhanga M L 1993 Future energy development in Tanzania. The energy costs of urbanization *Energy Policy* **21** 524–42

Hosonuma N, Herold M, De Sy V, De Fries R S, Brockhaus M, Verchot L, Angelsen A and Romijn E 2012 An assessment of deforestation and forest degradation drivers in developing countries *Environ. Res. Lett.* **7** 044009

Hurtt G C, Pacala S W, Moorcroft P R, Caspersen J, Shevliakova E, Houghton R A and Moore B I I I 2002 Projecting the future of the US carbon sink. Proceedings of the National Academy of Sciences, 99(3), pp.1389-1394.

ICF 2012 The DHS Program STATcompiler. Funded by USAID. http://www.statcompiler.com. [Last accessed 06, 20, 2020].

Instituto Nacional de Estadística de Moçambique. Projecções da População. (In Portuguese). [ONLINE] Available at: http://www.ine.gov.mz/estatisticas/estatisticas-demograficas-e-indicadores-sociais/projeccoes-da-populacao (Last accessed 06, 20, 2020).

International Energy Agency 2014 Africa Energy Outlook. A focus on the energy prospects in sub-Saharan Africa *World Energy Outlook Spec. Report, Int. Energy Agency Publ.* 1–237

International Energy Agency 2019 Africa Energy Outlook 2019 – Analysis Scenarios *Africa Energy Outlook 2019* 7

Kissinger, G., M. Herold V D S 2012 *Drivers of Deforestation and Forest Degradation: A Synthesis Report for REDD+ Policymakers* (Vancouver, Canada)

Lasslop G, Coppola A I, Voulgarakis A, Yue C and Veraverbeke S 2019 Influence of Fire on the Carbon Cycle and Climate *Curr Clim Change Rep*. **5** 112–23

Leach G and Mearns R 1988 Beyond the woodfuel crisis: people, land and trees in Africa

Luz A C, Baumert S, Fisher J, Grundy I, Matediane M, Patenaude G, Ribeiro N, Ryan C, Vollmer F and Woollen E 2015 Charcoal production and trade in southern Mozambique: historical trends and present scenarios *World For. Congr. XIV*

Mearns R 1991 Beyond the Woodfuel Crisis: People, Land and Trees in Africa *Development Perspectives for the 1990s* (Palgrave Macmillan UK) pp 189–96

Mitchell A L, Rosenqvist A and Mora B 2017 Current remote sensing approaches to monitoring forest degradation in support of countries measurement, reporting and verification (MRV) systems for REDD+ *Carbon Balance Manag.* **12**

Moorcroft P R, Hurtt G C, and Pacala S W 2001 A method for scaling vegetation dynamics: the ecosystem demography model (ED). Ecological monographs, 71(4), pp.557-586.

Mwampamba T H 2007 Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability *Energy Policy* **35** 4221–34

Mwampamba T H, Ghilardi A, Sander K and Chaix K J 2013 Dispelling common misconceptions to improve attitudes and policy outlook on charcoal in developing countries *Energy Sustain. Dev.* **17** 75–85

Neigh C S R, Masek J G, Nickeson J 2013 High-resolution satellite data open for government research EOS Trans. 94 121–3

Planet 2017 Planet Imagery: Product Spesification *Planet* 96 Online: https://www.planet.com/products/planet-imagery/

Ribot J 1999 A history of fear: imagining deforestation in the West African drylan forests *Glob. Ecol. Biogeogr.* **8** 291–300

Satterthwaite D, McGranahan G and Tacoli C 2010 Urbanization and its implications for food and farming *Philos. Trans. R. Soc. B Biol. Sci.* **365** 2809–20

Sedano F, Silva J A, Machoco R, Meque C H, Sitoe A, Ribeiro N, Anderson K, Ombe Z A, Baule S H and Tucker C J 2016 The impact of charcoal production on forest degradation: A case study in Tete, Mozambique *Environ. Res. Lett.* **11**

Sedano F, Lisboa S N, Duncanson L, Ribeiro N, Sitoe A, Sahajpal R, Hurtt G and Tucker C J 2020a Monitoring forest degradation from charcoal production with historical Landsat imagery. A case study in southern Mozambique *Environ. Res. Lett.* **15** 015001

Sedano F, Lisboa S, Duncanson L, Ribeiro N, Sitoe A, Sahajpal R, Hurtt G and Tucker C 2020b Monitoring intra and inter annual dynamics of forest degradation from charcoal production in Southern Africa with Sentinel – 2 imagery *Int. J. Appl. Earth Obs. Geoinf.* **92** 102184

Seto K C and Ramankutty N 2016 Hidden linkages between urbanization and food systems *Science (80-.).* **352** 943–5

Silva J A, Sedano F, Flanagan S, Ombe Z A, Machoco R, Meque C H, Sitoe A, Ribeiro N, Anderson K, Baule S and Hurtt G 2019 Charcoal-related forest degradation dynamics in dry African woodlands: Evidence from Mozambique *Appl. Geogr.* **107** 72–81

UN-Habitat 2014 *The State of African Cities 2014. Re-imagining sustainable urban transitions* (Nairobi, Kenya: UN-Habitat)

United Nations 2019 *World Urbanization Prospects. The 2018 Revision* vol 12 (New York) Online: https://population.un.org/wup/Publications/Files/WUP2018-Report.pdf

United Nations, Department of Economic and Social Affairs P D 2019 *Volume I: Comprehensive Tables* vol I Online: http://www.ncbi.nlm.nih.gov/pubmed/12283219 van der Werf G R, Randerson J T, Giglio L, Leeuwen T T van, Chen Y, Rogers B M, Mu M, Marle M J E van, Morton D C, Collatz G J, Yokelson R J and Kasibhatla P S 2017 Global fire emissions estimates during 1997–2016 *Earth System Science Data* **9** 697–720

Woollen E, Ryan C M, Baumert S, Vollmer F, Grundy I, Fisher J, Fernando J, Luz A, Ribeiro N and Lisboa S N 2016 Charcoal production in the mopane woodlands of Mozambique: What are the trade-offs with other ecosystem services? *Philos. Trans. R. Soc. B Biol. Sci.* **371**

Zulu L C and Richardson R B 2013 Charcoal, livelihoods, and poverty reduction: Evidence from sub-Saharan Africa *Energy Sustain. Dev.* **17** 127–37

Zulu L C 2010 The forbidden fuel: Charcoal, urban woodfuel demand and supply dynamics, community forest management and woodfuel policy in Malawi *Energy Policy* **38** 3717–30