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Estimating sustainable biomass harvesting level for charcoal production to promote degraded woodlands recovery: A case study from Mutomo District, Kenya

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Abstract

Charcoal is an important urban fuel; however, when production is unregulated, it is a major cause of land and forest degradation. Production through selective harvesting of the preferred large, hardwood tree species leads to a degraded residual forest or woodland composed of juvenile hardwood trees and unused softwood tree species. This situation can be addressed by ensuring that the rate of preferred tree species extraction does not exceed the mean annual increment. This study estimated the sustainable rate of tree harvesting for charcoal in Mutomo District, based on field data collected between December 2012 and January 2013, through a forest inventory. The woodlands are subjected to selective logging for charcoal production, an activity undertaken by about half of the residents for their livelihood. The study findings show that charcoal production through selective logging has led to a reduction of the hardwood trees biomass density to 3.8 t ha^{-1} compared with an estimated desirable level of 12.5 t ha^{-1}. The results also show that it would take between 25 and 31 years for the woodlands to recover to the desirable stocking level if harvesting was completely stopped. This duration would increase to between 54 and 64 years if 80% of the mean annual increment was harvested for charcoal production and 20% was retained for woodlands recovery. As the residents of Mutomo District are poor and highly dependent on charcoal production for their livelihood, a harvesting plan based on the latter option would set the woodlands on the path to recovery and ensuring a sustainable livelihood source.

KEYWORDS

dry woodlands, mean annual increment (MAI), selective logging, sustainable biomass, sustainable charcoal

1 | INTRODUCTION

In Sub-Saharan Africa (SSA), the demand for energy from biomass continues to rise due to high levels of poverty (May-Tobin, 2011) and a lack of alternative energy sources. More than 80% of the households in the fast-growing urban centers of SSA already use charcoal as the primary energy source for cooking (Zulu & Richardson, 2012). In the coming decades, charcoal demand is expected to grow fast with projections showing it could double by 2030 from the 1970s levels (Arnold, Koehlin, & Persson, 2006; Maes & Verbist, 2012; Zulu & Richardson, 2012). This increasing demand is postulated to exert more pressure on the available forest resources as deforestation and forest degradation have already been attributed to charcoal production around urban centers (Arnold et al., 2006).

Charcoal is produced either through clear cutting where almost all trees regardless of species are used or selective harvesting where only large sized trees of preferred species are felled (Chidumayo & Gumbo, 2013). Clear cutting is mostly carried out in land earmarked for agricultural expansion (Arnold & Persson, 2003). Chidumayo and Gumbo (2013) point out that clear cutting is prevalent in Eastern and Southern Africa, at least on a small spatial scale, whereas in West Africa, selective cutting is more common. However, selective logging is also practiced in Eastern Africa mostly by subsistence charcoal producers, especially in the drier regions (Kiruki, van der Zanden, Gikuma-Njuru, & Verburg, 2017; Ndegwa, Nehren, Grüninger, Iiyama, & Anhuf, 2016). Ndegwa, Nehren, et al. (2016) for the case of Kenya, and Kouami, Yaovi, and Honan (2009) for Togo emphasise that in selection logging, tree selection for charcoal production is based on size and species preference, with hardwood trees over 20 cm diameter at breast height being the most preferred. Several studies in both Western and Eastern SSA demonstrate that trees with a diameter at breast height as low as 5 cm are also used, especially when the large trees have already been depleted and the price of charcoal remains high (Chidumayo & Gumbo, 2013; Hosier, 1993; Kouami et al., 2009).

There is little information available on the ecological impact of selective logging for charcoal production on the dry forests and woodlands. This is mostly due to methodological and data collection constraints (Archibald & Scholes, 2007; Chidumayo & Gumbo, 2010; De la Barreda-Bautista, López-Caloca, Couturier, & Silván-Cárdenas, 2011). On the one hand, recent studies carried out in Kitui County in Kenya by Kiruki et al. (2017) and Ndegwa, Nehren, et al. (2016) demonstrated that charcoal production through selective logging leads to depletion of preferred species and adverse changes in overall forest composition. On the other hand, research has shown that dry woodlands, which had been degraded through selective logging, have the capacity to recover to a near original state (Butz, 2013; Murphy & Lugo, 1986). Furthermore, selective harvesting if well managed may have a positive impact on forest and woodlands recovery and charcoal prices as Hosier (1993) demonstrated. This is because it allows the woodland resource to recover between bouts of selective depletion and helps keep charcoal prices to a minimum through guaranteed continuous supply.

Recovery of depleted woodlands after selective logging depends on the intensity of harvesting and the climatic and edaphic conditions of the site (Aabeyir, Adu-Bredu, Agyare, & Weir, 2016; Hosier, 1993; Hosier & Milukas, 1992). Favorable climatic conditions and less intense logging promote quicker recovery (Hosier, 1993; Hosier & Milukas, 1992). Moreover, the residual vegetation provides ground cover that minimizes soil degradation through soil erosion and reduced water infiltration (Hosier, 1993). Based on a study in Western Kenya, Otuoma et al. (2011) state that to avoid further degradation and promote recovery of degraded woodlands, the tree offtake should not exceed the annual biomass increment commonly referred to as the Mean Annual Increment (MAI). In their study area, Otuoma et al. (2011) recommend a removal rate that does not exceed 80% of the MAI to promote woodland recovery.

To address the challenges emanating from unregulated charcoal production and trade in Kenya, the government enacted the Charcoal Rules, 2009 (Republic of Kenya, 2009), which among other things require the producers to form associations, through which they become licensed (wa Gathui, Mugo, Ngugi, Wanjiru, & Kamau, 2011). Other conditions they should meet to qualify for licensing are (a) a description of where the charcoal will be produced, the type and volume of trees to be used, and the carbonisation technology; (b) development of a reforestation/conservation plan that outlines how the cut trees/shrubs will be replaced and managed; and (c) a clearance from the local environment committee that is mandated to assess the environment situation in the area to avoid land degradation (County Government of Kitui, 2014; Luvanda, Kitheka, Oduor, Kyalo, & Githiomi, 2016; wa Gathui et al., 2011). However, the charcoal rules do not specify how the sustainable tree harvesting threshold is to be set and monitored, which leaves a loophole that can be exploited by corrupt environment committee members when giving clearance. The lack of a monitoring framework is due to the absence of data on available charcoal feedstock and a suitable methodology to set the sustainable harvesting limits for different forests and woodlands (GOK, 2013).

To date, the Charcoal Rules (2009) remain largely unenforced in many parts of the country and some of the stakeholders do not even know of their existence (Iiyama et al., 2014; Luvanda et al., 2016). This situation is due to corruption, inconsistencies in the regulations, and delays in issuing of production licenses (Iiyama et al., 2014; Maitai, 2014). The Charcoal Rules (2009) have therefore not been able to address the sustainability challenges they were formulated to solve.

Thus, to stop woodlands degradation in Kenya, a management plan that promotes sustainable production and harvesting of trees that is in line with the Charcoal Rules (2009) is needed. Moreover, national standards, guidelines, and monitoring mechanisms for sustainable tree harvesting have to be established. This in turn requires an estimation of sustainable charcoal biomass harvesting levels based on the available stock that is not available in Kenya so far. This study aims at addressing this gap by (a) proposing a methodology for estimating the sustainable hardwood trees biomass for charcoal production based on the initial stocking density and MAI using Mutomo District as our case study area, and (b) estimating how long it would take for the woodlands to recover under different harvesting intensities.

The data used in this study were collected in Kitui County in Eastern Kenya where dry woodlands have been unsustainably subjected to selective logging of hardwood tree species for charcoal production (Kiruki, van der Zanden, Malek, & Verburg, 2016; Ndegwa, Nehren, et al., 2016), an activity undertaken by about half of the residents for their livelihood (Ndegwa, Anhuf, Nehren, Ghilardi, & Iiyama, 2016). This study presents the basis that can be used to set the sustainable harvest levels based on the forests MAI to the stakeholders, including the charcoal-dependent households, the Kenya Forest Service (KFS), and the county governments.

2 | METHODS

2.1 | Study area

The study was conducted in Mutomo District that is located in Kitui County, Eastern Kenya. It has an area of 20,402 km^2, of which 6,290 km^2 and 1,833 km^2 are located within Tsavo East National Park and South Kitui National Reserve, respectively. Although Tsavo East National Park is under the full management of the Kenya Wildlife Services and is fenced to prevent human–wildlife conflict, South Kitui

National Reserve is under the administration of the county government and is not as secured as the National Park. This means that the residents of Mutomo have free access for exploitation of natural resources within the national reserve, including charcoal production, although this is illegal.

Mutomo District experiences high temperatures ranging between 20 and 34 °C and low precipitation of 500 to 1,050 mm per annum with 30% reliability (GOK, 2009). For this reason, it is categorised as arid and semi-arid lands with limited agricultural potential (Muyanga, 2005). The district has a population of about 180,000 people living in 32,896 households (Ndegwa, Anhuf, et al., 2016). The majority of the population practice small-scale subsistence rain-fed agriculture that can hardly sustain them (Kiruki et al., 2016; Ndegwa, Anhuf, et al., 2016). Therefore, charcoal production, which started in the late 1990s on a small scale as a coping strategy against drought, is currently undertaken by over half of the households (Ndegwa, Anhuf, et al., 2016). On the basis of rough estimates from the KFS, about 600,000 bags of charcoal, about 35 kg each, are produced in Mutomo District per year (GOK, 2013; Ndegwa, Anhuf, et al., 2016), with almost all of the charcoal coming from the lower parts bordering two main conservation areas (Figure 1). However, the KFS does not give the basis for this estimate, and its validity is questioned in the discussion section of this paper.

Mutomo District belongs to the *Acacia*–*Commiphora* Bushland and Thicket ecoregion as part of the tropical and subtropical grasslands, savannas, and shrublands biome according to the World Wildlife Fund classification of terrestrial biomes and ecoregions (Olson et al., 2001). It is dominated by *Acacia* and *Commiphora* tree species interspersed by other species such as *Combretum sp*, *Balanites sp*, *Boscia sp*, *Grewia sp*, *Terminalia sp*, *Maena sp*, and *Lannea sp* (Ndegwa, Nehren, et al., 2016). The *Acacia* species, among other hardwood trees, are specifically targeted for charcoal production whereas the *Commiphora* species and other softwood trees are mostly left standing. This selective felling has resulted in a remnant forest with dominant softwood tree species (Ndegwa, Nehren, et al., 2016). The data used in this study was collected between December 2012 and January 2013, to assess the impact of charcoal production on the dry woodlands. The study used the FAO (2002) land-cover classification through which the woodlands were divided into four main categories: open trees, thickets, shrubs, and herbaceous vegetation (Table 1). The classification was further verified on the ground during field work and was found to be largely accurate. Due to low population density, aridity, and lack of irrigation facilities, very little new land is opened up for cultivation or put under alternative land uses with much of perturbation on the natural woodlands being charcoal driven. The thickets are the most extensive forest land cover in the district and account for about 53.5% (82,896 ha), followed by shrubs at 33.8% (52,261 ha) of the total dry forest area. According to the findings of Ndegwa, Nehren, et al. (2016), the majority of the trees harvested were used for charcoal production.

2.2 | Estimating the sustainable level of tree harvesting for charcoal production

The standing hardwood trees biomass stock for each land cover class was estimated using the respective basal area as shown in Table 1. The biomass estimation equation recommended by Brown (1997) for dry zones with rainfall less than 900 mm per annum was used to calculate the biomass volume (dry basis) from the basal area (see Equation 1).

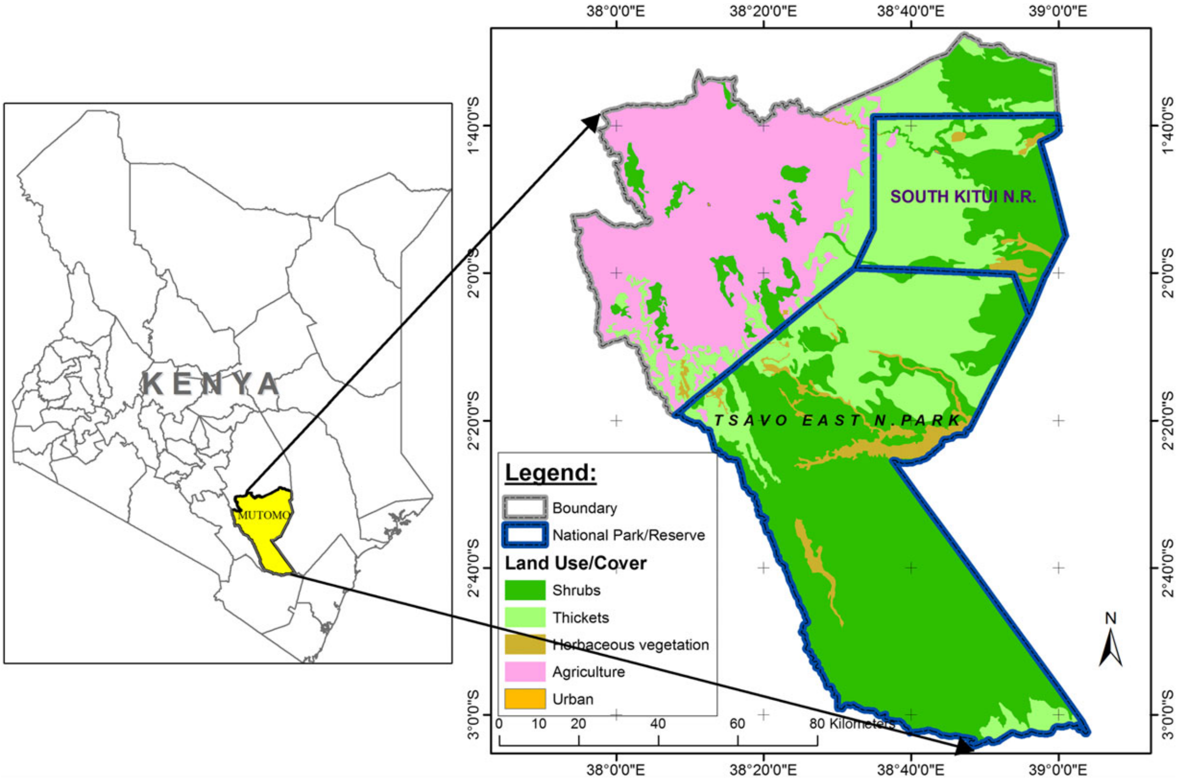

FIGURE 1 Map of Mutomo District showing land-use cover classes and protected areas [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Total available hardwood biomass in Mutomo District outside protected areas

Land cover class	Total area per ha (percent of total)	Basal area per hectare (m^2)	HW basal area per hectare (m^2)	SW basal area per hectare (m^2)	HW trees biomass		SW trees biomass	
					Per hectare (t)	Total (t)[a]	Per hectare (t)	Total (t)
Open trees	16,342 (10.5)	11.3	1.5	9.8	4.4	71,514.9	28.6	467,381.2
Thickets	82,896 (53.5)	5.5	0.9	4.3	2.6	217,658.7	12.5	1,036,200.0
Shrubs	52,261 (33.8)	6.0	1.8	5.1	5.3	274,441.8	14.9	7,786,88.9
Herbaceous vegetation	3,326 (2.1)	2.7	1.0	1.7	2.9	9,703.4	5.0	16,630.0
Total[a] (average)	154,825	(6.4)	(1.3)	(5.1)	(3.8)	588,335.0	(14.9)	2,306,892.5
Desirable level	154,825	(9.4)	4.3	5.1	12.5	1,935,312.5	14.9	2,306,892.5

Note. HW = hardwood; SW = softwood.

[a] Calculated by multiplying the biomass per hectare by area of respective land-cover class and dividing the result by the total area.

$$Y = 10^{*}\left[10^{\{-0.535+\log_{10}(BA)\}}\right], \tag{1}$$

where Y = biomass (oven dry) in tonnes and BA = basal area.

Charcoal production takes place in traditional earth mound kilns where wood is systematically piled on the ground and then covered with grass and soil (Chidumayo & Gumbo, 2010). The recovery rate of this kiln is estimated to be 20–30% on an oven-dry weight basis (Schenkel, Bertaux, Vanwijnbserghe, & Carre, 1998). The potential of charcoal production (in tonnes) in the district was therefore estimated using 25% as the average recovery rate. As charcoal is usually packaged and sold in standard sacks weighing about 35 kg (Ndegwa, Anhuf, et al., 2016), the potential production was converted into sacks by dividing by 35.

In order to estimate the hardwood trees biomass increment trend, the authors adopted the compound interest model for annual growth and increase in dry weight proposed by Blackman (1919) as shown in Equation 2. The principle amount (P) and interest rate (r) were substituted with initial standing stock (Y) and MAI, respectively, to obtain Equation 3 that was then used to model the relationship between MAI and biomass increment under a no-harvest scenario.

$$A_k = P^{*}(1+r)^{k}, \tag{2}$$

where A_k = amount at year or period k, P = principle amount, and r = interest rate.

$$Y_n = Y_i^{*}(1+\mathrm{MAI})^{n}, \tag{3}$$

where Y_n = hardwood trees biomass per hectare at year n, Y_i = initial hardwood trees biomass per hectare, and MAI = mean annual increment, in this case 4% of the standing stock.

The current MAI of dry forests in Mutomo District and Kitui County as a whole has not yet been established. Mortimore (1992) roughly estimated the MAI of dry woodlands in Machakos District in Eastern Kenya to be about 4% of the standing stock, whereas Enghoff et al. (2010) used a rough estimate of 4.8% for a study of dry woodlands in Daadab. Both of these woodlands are located in a similar agroecological zone as the woodlands in Mutomo District. In a study conducted in Kitui County where Mutomo is located, Hayashi (1992) reported that the growth rate of hardwood trees such as *Acacia mellifera*, *Acacia senegal*, *Acacia tortilis*, and *Acacia nilotica* is comparable with that of softwood tree species such as *Commiphora africana* and *Lannea triphylla*. As such, one can use the same MAI rate to estimate the increment of both hardwood and softwood trees. Without any scientifically established MAI for the study area, the authors used the 4% reported by Mortimore (1992) and the 4.8% reported by Enghoff et al. (2010) as the minimum and maximum MAI for the woodlands, respectively. These figures also lie within the 4–7% for the degraded coppicing woodlands in the Miombo woodlands in Tanzania reported by Malimbwi, Misana, Monela, Jambiya, and Nduwanungu (2001).

In order to model the biomass increment trend when a certain percentage of MAI is harvested for charcoal production, Equation 3 was further modified to obtain Equation 4. Assuming an average distribution of 46% hardwood tress basal area and 54% softwood trees basal area as per the findings of Ndegwa, Nehren, et al. (2016) in the undisturbed Tsavo East National Park, the models were used to estimate the number of years it would take for the standing hardwood trees biomass stock to attain this distribution under different harvesting intensities of the MAI. The modelling was done with the assumption that the current softwood trees basal area of 5.1 m^2ha^{-1} that is equivalent to 14.9 t of biomass (see Table 1) is the desirable stocking level as softwood trees are not targeted for charcoal production. A desirable stocking level, according to Gingrich (1967), is a relative term describing the density of a forest stand that adequately meets a certain management objective.

$$Y_n = Y_i + \left(\left(\left(Y_i^{*}(1+\mathrm{MAI})^{n}\right)-(Y_i)\right)^{*}(1-k)\right), \tag{4}$$

where Y_n = hardwood trees biomass per ha at year n; Y_i = initial hardwood trees biomass per ha; MAI = mean annual increment of the standing stock; and k is the percentage of increment biomass harvested.

3 | RESULTS

The study results show that the open trees land cover class has the highest tree basal area at 11.3 m^2ha^{-1} followed by the shrubs land cover class at 6.0 m^2ha^{-1} and thickets land cover class at 5.5 m^2ha^{-1} (Table 1). The results also show that the average tree basal area in the study area stands at 6.4 m^2ha^{-1}. Based on the assumption that the ratio between the hardwood and softwood trees biomass in the undisturbed woodland is 46:54, as explained in Section 2, the desirable biomass stock would be 9.4 m^2ha^{-1} (Table 1). The current basal area is therefore about two thirds of the desirable level for the woodlands in Mutomo.

Hardwood trees, which are usually targeted for charcoal production, have a quite low basal area in all the land cover classes compared with the softwood trees that are mostly left standing. The highest hardwood trees basal area is found in the shrubs land cover class at 1.8 m^2ha^{-1} followed by the open trees land cover class at 1.5 m^2ha^{-1} (Table 1). The average hardwood trees basal area is 1.3 m^2ha^{-1} that is less than a third of the desirable level of 4.3 m^2ha^{-1} as shown in Table 1.

The average hardwood trees biomass in the study area stands at 3.8 t ha^{-1} (Table 1), translating to 588,335 t of hardwood trees biomass in the unprotected part of the district (154,825 ha) where people reside and produce charcoal freely. The average softwood trees biomass stands at 14.9 t ha^{-1} that translates to 2,306,893 t in the unprotected part of the district. At the set desirable stocking level of 12.5 t of hardwood trees biomass per hectare, the woodlands in Mutomo District would have almost 2 million t of hardwood trees biomass (Table 1).

In order to promote the recovery of the woodlands to the desirable stocking level, a sustainable harvesting plan, which ensures that the quantity of hardwood trees biomass harvested is lower than the MAI, has to be adopted. The harvesting plan based on the MAI of the hardwood trees biomass shows that the higher the percentage of MAI biomass harvested per annum, the longer the woodlands would take to attain the desirable 12.5 t of hardwood trees biomass per ha (Figure 2). Taking the minimum MAI as the 4.0% adopted by Mortimore (1992), when no biomass is harvested for charcoal production, the woodlands would take about 31 years to recover (Figure 2). The recovery duration increases to 81 years when 90% of the MAI hardwood trees biomass is harvested. If we took the maximum MAI as the 4.8% adopted by Enghoff et al. (2010), the woodlands would take about 25 years to recover when no biomass is harvested (Figure 2). If, however, 90% of the MAI biomass is harvested for charcoal production, the recovery period would increase to 68 years. The minimum and maximum recovery periods when 80% of the hardwood trees biomass is harvested for charcoal production as recommended by Otuoma et al. (2011) are 54 and 64 years, respectively.

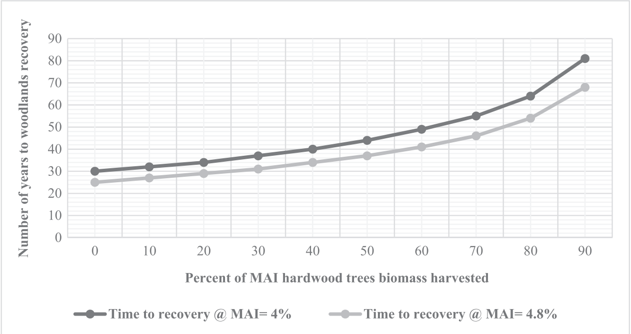

FIGURE 2 Number of years it would take for the woodlands to recover at different harvesting rates

Under a harvesting plan similar to that recommended by Otuoma et al. (2011), the total increment hardwood trees biomass raises gradually to between 77,000 (Table 2a) and 93,000 t (Table 2b) at full recovery when the hardwood trees biomass stocking gets to 12.5 t ha^{-1}. At full recovery, if 80% of the increment biomass was harvested and carbonised in an earth-mound kilns with a recovery rate of 25%, it would yield between 15,500 and 18,500 t of charcoal. This would translate to between 442,000 and 531,000 sacks of charcoal annually for the local charcoal producers.

4 | DISCUSSION

The main aim of this study was to propose a methodology for estimating the sustainable hardwood trees biomass for charcoal production based on the initial stocking density and the MAI using Mutomo District as our case study. The compound interest model for annual growth and increase in dry weight proposed by Blackman (1919) proved to be a suitable tool for this exercise and can be applied in many other locations facing similar challenges. Indeed Husch, Beers, and Kershaw Jr. (2003) has also recommended the use of the compound interest model in estimation of forest MAI. This study, however, modifies the compound interest formula to be able to model the biomass trend when different proportions of the MAI are harvested annually to produce charcoal as is the case in the study area.

Selective harvesting for charcoal production in the study area targets hardwood tree species, leading to massive depletion. The current stocking standing is estimated to be 3.8 t ha^{-1}. This is slightly below a third of the set desirable stocking density of 12.5 t ha^{-1}. Ndegwa, Nehren, et al. (2016) were able to associate the depleted hardwood trees biomass in the area with charcoal production as areas with higher numbers of kilns had a lower biomass density. Another study by Kiruki et al. (2016) in the same area confirmed that charcoal producers target hardwood species, which produce charcoal that is more favoured by urban clients.

Overall, the woodlands have a total of 18.7 t of biomass per hectare that is considerably below the Intergovernmental Panel on Climate Change (IPCC, 2006) estimates of 30 t ha^{-1} for tropical African dry woodlands (IPCC, 2006) and 32.9 t ha^{-1} as reported by Malimbwi, Solberg, and Luoga (1994) in Tanzania. However, it is comparable with the 21.7 t ha^{-1} reported by Sawe, Munishi, and Maliondo (2014) in a similarly degraded Miombo woodlands in Tanzania and the 21.42 t ha^{-1} reported by Enghoff et al. (2010) in degraded woodlands around the Daadab refugee camp in Kenya. If the woodlands were to recover to the desirable level estimated in this study, the overall standing biomass would raise to 27.4 t ha^{-1}, a figure comparable with the IPCC (2006) estimate.

The total available hardwood trees biomass in the study area is only 588,335 t. At the estimated minimum (4.0%) and maximum (4.8%) MAI, this would yield between 23,500 and 28,000 t of hardwood trees biomass in 1 year. If all increment hardwood trees biomass were harvested for charcoal production, it would yield between 168,000 and 202,000 sacks of charcoal, each weighing 35 kg. With Mutomo District reported to produce about 600,000 sacks of charcoal per annum (GOK, 2013; Ndegwa, Nehren, et al., 2016), this would

TABLE 2A Estimated sustainable charcoal production from available biomass at 4.0% MAI

Year	HW trees biomass per ha (t)	Total HW trees biomass (t)[a]	Increment HW trees biomass (t)	Total charcoal yield from 80% increment biomass (t)	Total charcoal yield from 80% increment biomass (35 kg bags)
0	3.80	588,335.0	0.0	0.00	0
5	3.96	613,107.0	24,524.3	4,904.9	140,139
10	4.16	644,072.0	25,762.9	5,152.6	147,216
15	4.41	682,778.3	27,311.1	5,462.2	156,064
20	4.71	729,225.8	29,169.0	5,833.8	166,680
25	5.07	784,962.8	31,398.5	6,279.7	179,420
30	5.50	851,537.5	34,061.5	6,812.3	194,637
35	6.04	935,143.0	37,405.7	7,481.1	213,747
40	6.69	1,035,779.3	41,431.2	8,286.2	236,750
45	7.48	1,158,091.0	46,323.6	9,264.7	264,707
50	8.44	1,306,723.0	52,268.9	10,453.8	298,680
55	9.61	1,487,868.3	59,514.73	11,903.0	340,084
60	11.04	1,709,268.0	68,370.72	13,674.1	390,690
64.3	12.50	1,9353,12.5	77,412.5	15,482.5	442,357

Note. HW = hardwood.

[a] Biomass per hectare multiplied by the total woodlands area (154,825 ha).

TABLE 2B Estimated sustainable charcoal production from available biomass at 4.8% MAI

Year	HW trees biomass per ha (t)	Total HW trees biomass (t)[a]	Increment HW trees biomass (t)	Total charcoal yield from increment 80% biomass (t)	Total charcoal yield from 80% increment biomass (35 kg bags)
0	3.80	588,335.0	0	0	0
5	4.00	619,300.0	29,726.4	5,945.3	169,865
10	4.25	658,006.3	31,584.3	6,316.9	180,482
15	4.58	709,098.5	34,036.7	6,807.4	194,496
20	4.98	771,028.5	37,009.4	7,401.9	211,482
25	5.49	849,989.3	40,799.5	8,159.9	233,140
30	6.14	950,625.5	45,630.0	9,126.0	260,743
35	6.96	1,077,582.0	51,723.9	10,344.8	295,565
40	8.00	1,238,600.0	59,452.8	11,890.6	339,730
45	9.31	1,441,421.0	69,188.2	13,837.6	395,361
50	10.96	1,696,882.0	81,450.3	16,290.1	465,430
53.8	12.50	1,935,312.5	92,895.0	18,579.0	530,829

Note. HW = hardwood.

[a] Biomass per hectare multiplied by the total woodlands area (154,825 ha).

mean that around 400,000 sacks of the charcoal are unsustainably produced. This figure seems quite high and unrealistic given that charcoal is reportedly only made from hardwood trees that are highly depleted. Producing such a huge volume of charcoal from few dispersed hardwood trees would be tantamount to mining and would have to be driven by an exponential increase in price to make economic sense (Hosier, 1993). The charcoal producers encountered in the course of this study, however, reported a moderate increase in charcoal prices from about KSH300 to KSH400 (1USD≈ 101KSH) over the last decade. The theory that price increase has led to the reported high levels of production through wood mining can therefore be discounted. It is therefore important to explore the reason why there is such a huge discrepancy between the reported charcoal supply from Mutomo District and the estimated sustainable level.

There are several possibilities that might explain the huge discrepancy between the reported and the potential level of production calculated in this study. These possibilities are as follows: (a) There is gross overestimation of the charcoal production in the area; (b) Charcoal is not exclusively produced from hardwood tree species; and (c) Charcoal sourced from surrounding areas is reported to originate from Mutomo.

With respect to the first possibility, the figures quoted by Ndegwa, Nehren, et al. (2016) were reported in a KFS report (GOK, 2013) that stated about 1 million bags of charcoal originate from Kitui County every year, whereas a local forest officer stated that about 60% of this quantity comes from Mutomo. On closer examination of the report, one finds that the figure was reported without enumerating the methodology, presenting empirical evidence, or even a credible source of this information. As such, the figure could be greatly exaggerated and misleading. This issue of lack of credible data on wood fuel in general has been put forward by many researchers, especially in Africa (Arnold & Persson, 2003; Drigo, 2005; Iiyama et al., 2014). Lack of credible data was also blamed for underestimation of the forest and woodland productivity and grossly overestimated wood fuel consumption levels that led to declaration of an impending wood fuel crises in Africa in the 1980s that never came to pass (Arnold & Persson, 2003; Chidumayo & Gumbo, 2010; Mwampamba, 2007).

Regarding the second possibility, research has shown that when the preferred charcoal species are depleted, the charcoal producers will be forced to use lower quality readily available tree species to meet the prevailing demand (Chidumayo & Gumbo, 2013; Hosier, 1993; Kouami et al., 2009). With continued depletion of the preferred hardwood species in the study area, some charcoal producers were reported to mix the available hardwood trees feedstock with some softwood trees species feedstock, which is in line with the above-named authors' observations. The charcoal producers, however, reported that charcoal with a high percentage of softwood feedstock was easily identified by the buyers and fetched lower prices. For this reason, the affected producers added only a small quantity of softwood trees biomass that can be easily disguised. Therefore, it is clear that softwoods, through mixing with hardwoods, are used in charcoal production in the study area. However, the overall quantity of softwood feedstock used is quite low as these would have to be mixed with the hardwoods, which are limited in quantity. Thus, the contribution of softwood trees cannot be exclusively responsible for the high discrepancy.

Finally, a quick look at the land cover map of the study area (Figure 1) shows that the majority of the remaining woodlands are in conservation areas, namely, South Kitui National Reserve and Tsavo East National Park. Much of the woodlands where the community is settled have already been depleted or converted to agricultural land. Although Tsavo East National Park is fenced, limiting human encroachment, South Kitui National Reserve is not. In 2013, KFS reported alarming illegal charcoal production activities in the reserve, mostly by people from outside Mutomo District (GOK, 2013). Some of the charcoal is also produced from the neighbouring Garissa and Tana River counties and transported through Kitui. In the course of this study, the local forest officers reported that up to 50% of the charcoal reported as produced in Mutomo District could actually be coming from the national reserve and neighbouring counties. It is therefore very likely that there is a substantial amount of charcoal produced from woodlands outside the studied area and reported to come from Mutomo District that could lead to the inflated figure.

The authors' conclusion is therefore that the figure of 600,000 sacks of charcoal reported to originate from Mutomo District is highly exaggerated as no quantitative study has been done to ascertain these figures. However, the actual amount of charcoal originating from Mutomo District could be significantly higher than the sustainable potential calculated in this study due to unsustainable harvesting of hardwood trees biomass and use of softwood trees in charcoal production. According to Hosier (1993) and Murphy and Lugo (1986), unsustainable selective harvesting has the potential to alter the overall composition of the woodland although soil degradation is unlikely to occur if the understorey vegetation is not cleared. When the soils are only minimally impacted, the degraded woodlands will eventually recover, but the rate of recovery will depend on the climatic factors and harvesting and postharvest management practices (Aabeyir et al., 2016; Hosier, 1993; Hosier & Milukas, 1992).

Ndegwa, Anhuf, et al. (2016) and Kiruki et al. (2016) reported that charcoal production is an important livelihood source for many poor residents of Mutomo District who have no alternative sources of income. As such, addressing the problem of woodland degradation would require an innovative approach that does not compromise on the livelihoods of these poor people. The Charcoal Rules, 2009 and the Kitui County Charcoal Management Act (County Government of Kitui, 2014) set a condition that all prospective charcoal producers must harvest wood sustainably and at the same time adopt a reforestation and tree management plan that ensures continuous supply of charcoal feedstock and guards against deforestation/woodland degradation (Maitai, 2014; wa Gathui et al., 2011). Although this directive is not implemented, partly due to lack of a methodology to set the threshold, pegging the sustainable harvesting level based on the woodlands, MAI can effectively address this problem.

Setting up a tree offtake level is a complex undertaking as conservation would require retention of close to 100% of the MAI whereas the charcoal producers would want maximum possible access (Otuoma et al., 2011). As such, Otuoma et al. (2011) recommends an offtake of 20% of the MAI. This would eventually lead to the woodland recovery and would be acceptable to the producers as it balances the conservation and consumptive needs of the society.

Lack of a scientifically established MAI increment for the woodlands was a big challenge when estimating the overall growth of the woodlands. Similar concerns were raised by Drigo (2005) who stated that estimating biomass growth in the East African region is a complex task that is aggravated by lack of reliable data. The two MAI estimates by Mortimore (1992) and Enghoff et al. (2010) that were applied in the same locality were adopted as they fall within the 4–7% range reported by Malimbwi et al. (2001) for the Miombo woodlands in Tanzania.

Results from this study show that if all woodland degrading activities, including harvesting for charcoal were halted, the woodlands would take between 25 and 31 years to recover. This is slightly above the 8 to 23 years reported by Malimbwi et al. (2001) that Miombo woodlands in Tanzania degraded through charcoal production took to recover when harvesting was halted. If 80% of the hardwood trees biomass is harvested for charcoal production, the woodlands would take between 54 and 64 years to recover. This is quite long compared with the 20 years reported by Otuoma et al. (2011) required for degraded dry woodlands in Western Kenya to recover when 80% of MAI biomass was harvested for charcoal production. The shorter duration reported by Otuoma et al. (2011) could be attributed to the fact that the remnant woodland in their case had a higher stocking density of the targeted species than that of the study area. The basal area of targeted species reported by Otuoma et al. (2011) was 9.7 m^2ha^{-1} compared with 4.8 m^2ha^{-1} in the study area.

If a harvesting plan where 80% of the MAI hardwood trees biomass for charcoal production was adopted, the potential amount of charcoal that could be produced would progressively increase to between 442,000 and 530,000 sacks per annum at full recovery. The woodlands would consequently be able to play a key role in livelihood support for the community without compromising on the provision of ecological services. However, it is important to note that even though selective logging has less impact on the woodlands compared with clear felling (Hosier, 1993), care must be taken when harvesting to avoid excessive damage to the residual vegetation (Chidumayo & Gumbo, 2010). The charcoal producers may also need to be trained on post-harvest management practices such as management of coppices, fertilisation, and shoot or sucker protection to ensure improved recovery rates (Hosier, 1993).

5 | CONCLUSION

This study demonstrates the extent to which targeted harvesting of charcoal production has reduced the hardwood stocking density in the study area. Hardwood trees that are usually targeted have been depleted whereas softwoods are mostly left standing. To address this challenge, the study has proposed a wood harvesting plan that would promote increment of hardwood trees and the recovery of the woodland as a whole. Even though there is a legal framework for sustainable charcoal production in Kenya and at the country level, a scientific basis to support the implementation of the respective laws is lacking. The study therefore presents a basis to the community and policy makers to set sustainable wood harvesting levels based on MAI of the woodlands. As the study has demonstrated that with time the woodlands have the potential to recover and supply much more charcoal than it is presently supplying, such a management plant would be readily acceptable to the society.

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