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Research article

Sustainable woodland management and livelihood options in a charcoal producing region: An agent-based modelling approach

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ABSTRACT

Woodland resources provide livelihoods for millions of people in Africa. Concerns about the impact of human utilization of woodlands have led to vigorous debates on woodland degradation. Ecological and socio-economic empirical data and understanding of the socio-ecological system have been synthesized in an agent-based model (ABM) to explore different woodland management options for a dynamic, semi-arid region in Kenya. In our simulations we accounted for the impacts of drought frequency, charcoal price changes, improved management practices and taxation of charcoal for a 20-year period to assess woodland changes in a spatially explicit way and evaluate the numbers of actors that can benefit from charcoal harvesting as a livelihood option.

The model is based on an agent typology derived from 150 household interviews that focused on livelihood strategies and decision-making processes. Furthermore, the model integrates knowledge from vegetation plots and focus group meetings. From the model simulations we learn that favorable prices, improved management and taxation do not directly have the anticipated impact on woodland resources, as the improved conditions lead to fewer constraints on involvement in charcoal making. This reduces the positive impacts of these measures on the woodland quality but, at the same time, allows a larger number of actors to benefit from charcoal harvesting. Results show a very strong decrease in woodland area under the base scenario thereby reducing possibilities for households to supplement their incomes with charcoal making. Increased droughts and low prices for charcoal lead to early depletion of woodlands and reduction in livelihood options. Taxation stabilizes the number of charcoal producers but does not stop the depletion of woodland area. Woodland loss can only be prevented by controlling the number of charcoal makers and the amount of charcoal harvesting.

1. Introduction

In many Sub-Saharan African countries, charcoal production is an important anthropogenic activity that generates income and supports livelihoods in rural areas by selective logging of charcoal species (Malimbwi and Zahabu, 2008; Butz, 2013). The role and importance of charcoal production in rural livelihoods has been well documented in Sub Saharan Africa. Charcoal production is important for supplementing incomes from other livelihood activities (Butz, 2013; Jones et al., 2016), for poverty reduction (e.g. Fisher, 2004; Schure et al., 2013) and as a coping strategy in times of shocks (Zulu and Richardson, 2013). While charcoal production is important in rural livelihoods, there are concerns on its sustainability and its effect on woodlands (Cerutti et al., 2015). Concerns about the impact of charcoal production have led to vigorous debates on the role of charcoal in woodland degradation and deforestation (see e.g. Zulu and Richardson, 2013; Aabeyir et al., 2016; Sedano et al., 2016). Some authors attribute deforestation purely to charcoal production (Monela et al., 1993; Oduori et al., 2011), while others argue that agriculture is the main driver of deforestation with charcoal being a by-product (Rueda et al., 2015). Charcoal production is mainly done through selective cutting, in which only key charcoal trees are harvested. This leads to degraded woodlands, as opposed to clear cutting that results in deforestation (Chidumayo and Gumbo, 2013). Charcoal led forest degradation and biodiversity loss due to selective harvesting of charcoal species has been reported by many authors in East Africa (e.g. see Namaalwa et al.,

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2007; Ahrends et al., 2010; Kiruki et al., 2017). Furthermore, as charcoal production is mostly an informal activity there are numerous constraints to its sustainable management (Schure et al., 2013; Iiyama et al., 2015).

In spite of its role in environmental degradation, charcoal is a major source of livelihood and it is produced by a wide range of people and for a variety of reasons. Previous research has shown that the scale and timing of production is closely linked to the situation and reasons for producing (Jones et al., 2016). Charcoal production is spread across individual land holdings, neighbouring farms and public lands. The charcoal producers also vary according to their scale of production ranging from those who produce a few bags to cater for a specific need to full-time commercial producers. Charcoal production is also dependent on climatic factors with dry months recording higher production (Kiruki et al., 2019). Therefore, charcoal production and its environmental impacts on woodlands can only be understood by accounting for the decision-making process of the charcoal maker, the variation amongst charcoal makers and the adaptation of charcoal making to climatic variation and change in markets and governance. For individual charcoal makers, the decision process is based on a host of factors such as perceived price changes, food scarcity, availability of preferred species, land ownership and age (Khundi et al., 2011; Schaafsma et al., 2012; Kiruki et al., 2019). There is variation in this decision-making process between actors and the actors are often competing for nearby woodland resources (Schaafsma et al., 2012). Due to this diversity and the dependence on woodland resources, outcomes in terms of woodland state and contribution to livelihoods are difficult to anticipate. Agent-based modelling (ABM) provides a suitable tool to represent these human-environment interactions and the diversity in decision-making amongst actors to explore the impacts on livelihoods and the woodland system in an integrated manner. For example, in order to understand the interactions between space, resources and stakeholders and to improve the resource-related decision-making processes, Bah et al. (2006) used ABM to simulate and understand multiple land uses around drillings in the Sahel and they demonstrated the effectiveness of ABM in understanding the interactions and dynamics of complex systems.

ABM is a technique that allows representation of charcoal makers as autonomous decision-making agents, while the woodlands from which they make charcoal are represented as spatial units. These characteristics give ABM the capacity to describe, simulate and analyse the interaction between charcoal makers and the woodlands. The appeal of ABMs lie in their ability to explore interactions between micro- and macro-level structures and incorporate the decision-making processes of heterogeneous agents (Sun et al., 2016). Agents make decisions using both prescribed rules and analytical functions (Bert et al., 2011) with the rules and specific process-response interactions between social and natural elements leading to complex emergent and often unpredictable spatial or temporal patterns of environmental change (Mialhe et al., 2012).

A lot of research has been invested in trying to understand why resource users behave the way they do and many decision-making theories, models and frameworks have been put forward, such as rational choice, bounded rationality, planned behaviour, heuristic and cognitive theories (Meyfroidt, 2013). In this study, we have used bounded rationality theory to explain the charcoal makers resource utilization strategy. Bounded rationality theory is based on real-world observations and studies and recognizes that decision-making is influenced by social context, limits of human knowledge, information processing abilities and multiple motives and values (Peterson, 2014). As part of this theory, resource use behaviors are linked more to prevailing cultures and contexts than pure benefits. These resource use behaviors are explained by social science theories and recently the concept of an efficient complexity manager has emerged in contrast to the rational actor (Levine et al., 2015). Resource users have different objectives and heterogeneous behaviour. When heterogeneous human behaviour drives a system in constant flux, homogeneous behavioural assumptions are unable to capture the critical dynamics of human–environmental interactions (Wise and Crooks, 2012). ABMs have the capacity to represent heterogeneity amongst agents, and model decision-making from the bottom-up so that emergent properties of the system can be analysed at an aggregate level such as the region or landscape (Brady et al., 2012).

The objective of this paper is to use ABM to explore the ways in which decision-making regarding charcoal production affects the spatial and temporal state of woodlands for a case study area in Kitui, South Eastern Kenya, which is a prominent charcoal producing area. More specifically, we use an agent-based model as a tool to integrate empirical understanding of decision-making on charcoal production by diverse agents and analyse how changes in the occurrence of drought, charcoal price and interventions to reduce charcoal-making intensity contribute to changes in the woodland structure and the number and types of actors that benefit from charcoal making for their livelihoods. Specifically we seek to answer the following research questions.

(i) What are the impacts of changing drought conditions on the woodland area and number of charcoal makers?
(ii) What are the effects of introducing taxation on woodland area and number of charcoal makers?
(iii) How does price increase of charcoal affect the woodland area and number of charcoal makers?
(iv) What are the effects of improved woodland management practices in combination with efficient kilns, on woodland area and number of charcoal makers?

An evaluation of these outcomes can serve as a first insight into the long-term effects of suggested interventions to improve the sustainability of the charcoal value chain, that have the aim to support both sustainable socioeconomic development, as well as environmental protection and conservation.

2. Methods

2.1. Description of the study area and the local livelihood options

The study was conducted in parts of the Mutha and Ndakani locations of Kitui County in Kenya, which is 150 km east of Nairobi and covering an area of 442 sq km (Fig. 1). According to KNBS (2010), the Mutha and Ndakani locations have a population of 10,154 people in 1865 households with an average density of 27 persons/sq. km (KCDP, 2013). The study area borders Tsavo East National Park to the West and Kitui South Game Reserve (KSGR) to the East. The area is semi-arid with rainfall of below 750 mm per annum (Eriksen et al., 2005). The vegetation of the study area is described as Acacia-Commiphora deciduos bushland and thicket within the Somalia-Masai ecoregion (Brink and Eva, 2011). The local economy depends on subsistence agriculture and livestock keeping.

Charcoal making to supplement income is prevalent in the area due to high poverty rates and low rainfall reliability leading to crop harvest failure and loss of domestic stock. The crops grown are mainly cereals and legumes. Due to low and unpredictable rainfall and subsequent low agricultural production, food scarcity is a permanent feature in the study area (Kiruki et al., in press).

2.2. Overview and design of the agent model

The purpose of the model is to explore how decisions of charcoal makers influence the woodland cover for a semi-arid region in Kenya under varying environmental and socio-economic conditions. We seek to explore the relationship between drought probability, charcoal price changes, woodland cover and the number and type of charcoal makers. The agent-based model is described using the ODD + D (Overview,

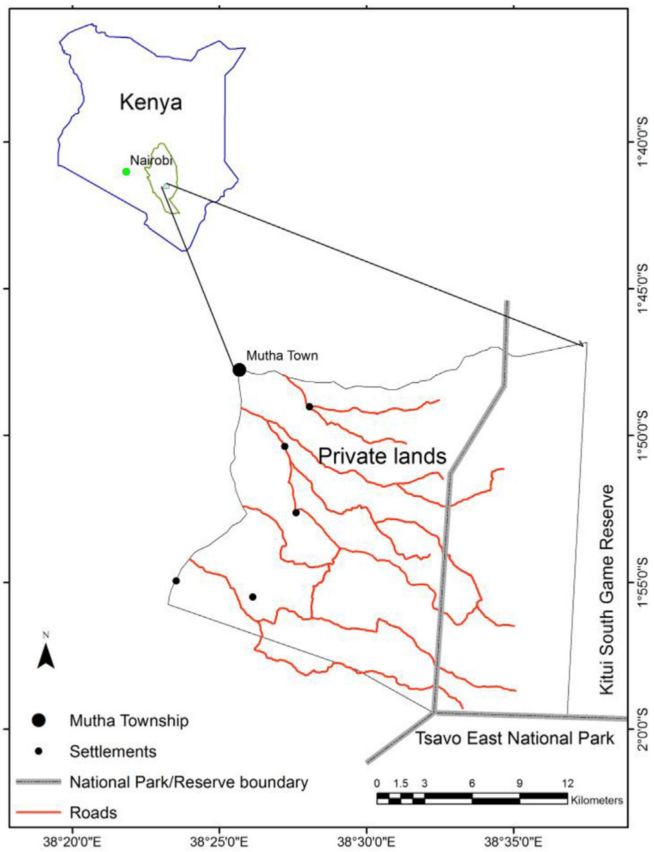

Fig. 1. Location of the study area in Kenya.

Design, Details and Decision) protocol in Supplementary materials 1, Appendix 1 (Müller et al., 2013).

In our model, individual households and woodland plots are the main entities. The agent decision model is based on the assumption that agents have limited information processing capacity on charcoal production and marketing dynamics, hence they have a bounded rationality Appendix 1. The state variables of households capture the livelihood options of each household. This includes social variables (age, gender) and economic variables (e.g. income sources)(see section 2.2.1).

2.2.1. *Charcoal maker identification and decision making survey*

A total of 525 charcoal-producing households spread in six villages in the study area were identified from village membership lists of the Mutha Charcoal Makers Association (MCMA) and village elders. We proportionately allocated our target sample size of 150 households to the six target villages and took a random sample from each village. Interviews were done in the local Kamba language by the author and 4 research assistants who grew up in the study area. The interviews were conducted between May and June 2016 and lasted approximately 1.5 h.

The interviews were based on a standard questionnaire with both open and closed questions relevant to the study and targeted at the household head. The questionnaire included quantitative questions on household characteristics, household income, and reasons for engaging in charcoal making and the location of charcoal making. Income figures are based on the informant's recall on all sources of cash and subsistence income for the previous year. This is a widely used survey technique for living standards assessment (McElwee, 2010). “What if” questions were also asked to elucidate the likely future actions of a household under various environmental and policy scenarios likely to face a household. These questions were directly translated into the agent-based modelling. An example of such a question is “*Will you change the amount of charcoal you make if the price of charcoal increases by ¼? If yes by how many bags per year?*”. Field observations complemented the interview responses and helped to cross-check the information provided. We developed a typology of charcoal makers based on the contribution of charcoal income to the total household income and the behaviour in charcoal production. Here, we based behaviour in charcoal production on the location of charcoal making and the time spent on charcoal production activities. Three types were distinguished with distinctly different strategies.

In addition to the household interviews, two focus group discussions were held in the study area in June 2017. These sessions consisted of 26 individuals in total. The aim of the focus groups was to give the researchers insight into the charcoal industry and identify possible measures to make charcoal harvesting and production more sustainable. The discussions centred on farmer managed regeneration, agroforestry – purposed tree planting on farms, the possibility of improved methods of charcoal production and effects of the recent requirement to join a charcoal producers associations (CPA) on charcoal production. Realistic ranges of the contribution of these measures to more sustainable management were identified and used in the model. Fig. 2 below summarises the data collected for use in agent modelling and the model outcomes.

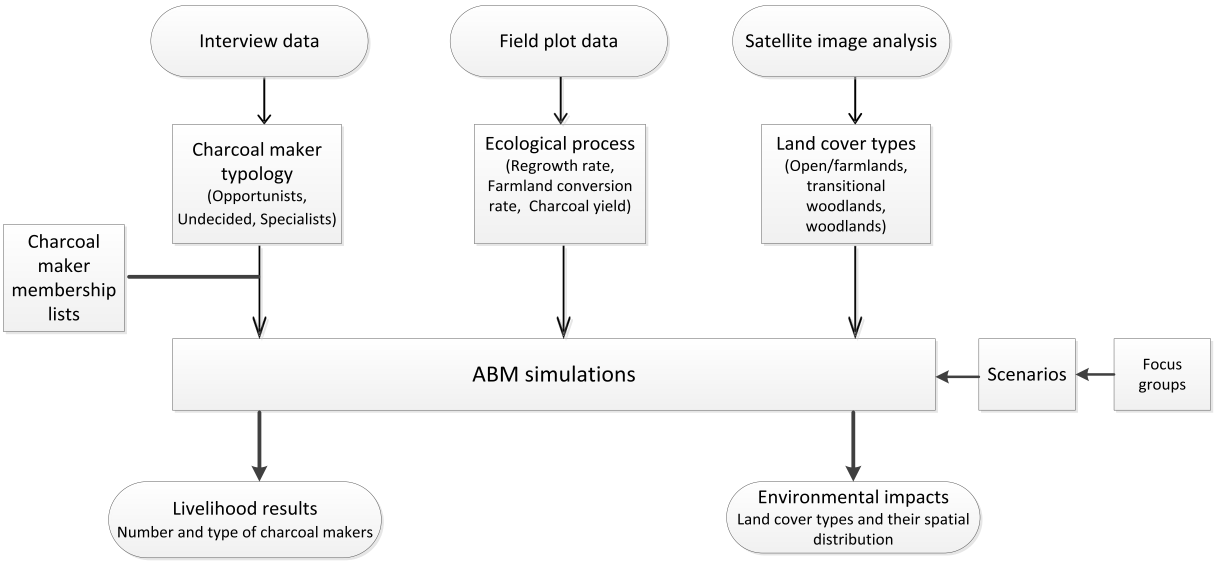

Fig. 2. Schematic representation of the model inputs data and the expected outputs.

We used the collected primary socio-economic data to build three charcoal maker typologies based on proportion of charcoal income to their total household income. The three levels of charcoal income dependency were derived from focus group discussions where charcoal makers in our study area were classified as opportunistic producers, undecided and specialists in an approach aimed at creating reasonably balanced groups. Following the method of Jain and Sajjad, 2016 and Garekae and Thakadu, 2017), we used the average proportion of charcoal income for all households as a rough guide, with households whose charcoal income is higher than this average being denoted as highly dependent. Households for which charcoal income contributes up to 10% of the total household income were designated as opportunists. These households make charcoal occasionally to supplement their income and only do so within the private lands, either their own land or their neighbours land. Households for which charcoal contributes between 10 and 25% of the total household income were designated as undecided. They have modest income from charcoal, agriculture and livestock keeping. They make charcoal on both private lands and the KSGR, even though charcoal production is illegal in the KSGR. Households for which charcoal income contributes > 25% of the total household income were designated as specialists, because charcoal is largest income source. The groupings were intuitively recognized by stakeholders in the area. The rules for each of the typologies were defined based on the proportion of charcoal income to total income, age, gender and location of charcoal making. Furthermore, the age of the household head defines how long s/he can continue to be involved in charcoal making. Gender determines where the household head can make charcoal, as women only make charcoal in the neighbourhood of the house while men are going further away to harvest.

In the model the agents are assumed to be satisficers and seek to achieve a certain minimum total income. This assumption is based on the interviews with charcoal makers and focus group discussions in the study area, who gave us a brief on how and why they undertake charcoal making (appendix 2). From our analysis, every charcoal maker has subconsciously set an income target to achieve for his/her household which can be achieved from a combination of strategies. This target minimum income per agent is the total household income calculated from questionnaires, which is a combination of income from all sources including charcoal. When this income is achieved, agents do not aspire to earn more. If the total income is less than what they aspire, they fill the difference by making charcoal. The fluctuation of income from agriculture, as well as the charcoal price, determine therefore how much charcoal a household makes in order to fill the income gap.

The state variables for the woodland plots are land cover class, location and charcoal yield. The plots are either farmlands, transitional woodlands or woodlands. The plots can transition from farmland to transitional woodlands to woodlands and back. The transition rates from woodland to farmland are based on analysis of satellite image from 1986 to 2014 and the observed annual rates are assumed to continue for the next 20 years. The transition rates from woodland to transitional woodlands are based on charcoal harvesting as computed within the model. The recovery of transitional woodlands to woodland is dependent on re-growth (appendix 2).

All the plots (pixels) are 1.233 ha in size and are located either on private land or in KSGR. The charcoal yield is initially set at 19 bags/ha, for woodland plots based on calculated dry biomass of charcoal producing species on the field plots sampled (appendix 2). In the study area a bag of charcoal weighs approximately 35 kgs (KFS, 2013). In order to represent all charcoal-producing households in the study area, we created, in addition to the 150 interviewed charcoal makers, a further 375 charcoal makers using Monte Carlo techniques. The household agents are spatially distributed in the landscape and the location of each of the 150 interviewed households represents its true position on the ground. The location of the created charcoal makers was random and was limited to the private lands as no settlements are allowed in the KSGR.

The model is programmed in Netlogo version 5.3.1 making use of its GIS extension (appendix 1 and section 2.3.1). The model runs on yearly time steps. At the start of each time step, charcoal makers belonging to opportunist and undecided types return to their home location and new charcoal makers are added at this stage as opportunists. For each time step, all agents calculate their income from agriculture, livestock and selling labour and compare it with their target minimum income for the year. Based on this calculation, a decision to engage in charcoal making or not is made. If the income from agriculture, livestock and selling labour is less than the target minimum income for the year, a decision on the amount of aspired charcoal income and the quantity to be produced is made. Charcoal making is an important household diversification and income gap filler strategy in many rural sub-Saharan Africa households (Smith et al., 2017; Brobbey et al., 2019). If an agent is not able to reach a sufficient woodland area to harvest charcoal (within the rules set for the agent type) leading to less income than aimed for in 3 consecutive years, the agent is assumed to stop engaging in charcoal production and exits the model. It is assumed that the exiting agents either find other livelihood options or migrate out of the area. Interviews with charcoal makers revealed that they will turn to other options, like involving in petty trades or seeking unskilled employment in towns out of the study area, if they don't make a livelihood from charcoal making. An agent whose charcoal production behaviour does not match the typology-defining thresholds for two consecutive years automatically changes to a charcoal-making type which more accurately reflects his/her current reliance on charcoal production. The probability of transitioning towards a more suitable charcoal-making type increases proportionately with each year that a household's charcoal dependency does not reflect that of its charcoal-maker type. This procedure allows agents to change their long-term charcoal-producing behaviour in response to changing circumstances, while also allowing for some initial resistance to modifying their preferred strategy as this results in a change in livelihood. Fig. 3 shows the flow diagram of the modelling process.

Based on the charcoal maker typology and gender of the charcoal maker, charcoal-making agents decide whether to make charcoal in private land or in KSGR. Gender is important for this decision, as the interviews showed that female charcoal makers only consider woodland areas which are near to their houses for charcoal making, so that they are able to attend to other household tasks such as looking after the children and their houses, in line with local cultural norms. They generally remain within 1.5 km from their homes and on private land since KSGR is considered unsafe for them. This distance was derived from interviews and scaled from the indicated distance to a comparable straight-line distance within the model. Men on the other hand tend to make charcoal further away from home if local tree resources are insufficient. They can either opt to make daily trips to their homes or stay in the field in small camps. This also explains why fewer women are charcoal makers. The charcoal maker typology also has influence on the location of charcoal making, as their charcoal making behaviour determined the classification: opportunists can only harvest charcoal within private land, while the undecided and the specialists harvest charcoal on both private land and KSGR. While opportunists and undecided actors return to their home plots at the beginning of each yearly harvest cycle and look for the closest harvest locations again, the specialists are assumed to look for new harvest opportunities for the next year closest to the location they were harvesting in the previous year. A specific sub-set of specialist charcoal-makers known as 'explorers' move to a different location at the beginning of each harvesting cycle, not necessarily close to that of the previous year, in hopes of finding more abundant, forested land elsewhere. These rules create a behaviour in which the specialists tend to reach out much further into the woodland for harvest locations than the opportunists and undecided, while the opportunists only take advantage of charcoal harvesting as long as sufficient resources are available within the private lands.

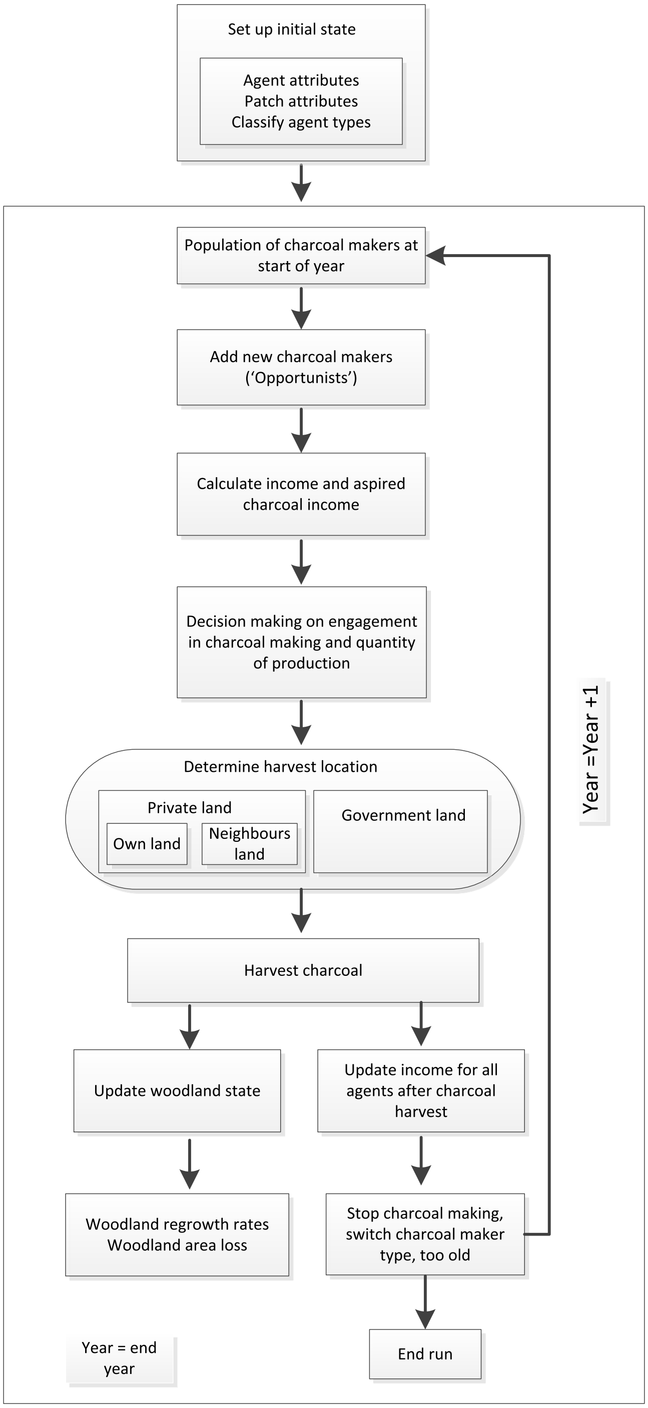

Fig. 3. Flow diagram of the modelling process for charcoal makers in Kitui, Kenya.

Livelihoods in semi-arid areas are marked by uncertainty due to volatile weather conditions which affect agricultural and livestock production. From empirical data, focus group discussions and interviews, we gather that droughts affect crop yield and livestock productivity and impoverishes households by reducing their income and increased dependency on charcoal. For instance, income from farm labour also reduces as there is no paid work to be done at the farms. The focus groups consisted of village elders, charcoal makers and individuals who were active in community activities, as identified by the assistant chief (lowest official in provincial administration in Kenya). In the model, droughts occur randomly and reduce agricultural production by approximately 30% (appendix 2). The probability of droughts occurring in the area is currently 50%. If the probability of droughts increases, then it results in more dependence on charcoal as the number of years with reduced crop yields increases as well. In other words, more agents will transition from opportunists to undecided and specialists.

2.3. *Data collection methods*

2.3.1. *Land use conditions and vegetation survey*

A land cover map for the study area was generated using Landsat satellite images for the year 2014 and processed using ENVI 5.1 and ERDAS imagine 9.1 software. The image was clustered to 20 classes with common reflectance which were later reclassified to 3 pre-determined classes based on knowledge of the area. The three resulting classes are woodlands, transitional woodlands (i.e., degraded woodlands through deforestation) and farmland/open areas (for detailed on the methods, see Kiruki et al., 2016).

In the case study area, charcoal production only occurs in the woodland areas. To assess the charcoal harvest potential, a systematic vegetation sampling was done on five parallel transects of sixteen km long and 1 km apart. Along the transects, plots measuring 0.1 ha were placed 1 km apart. In total 75 plots were sampled. Within the 0.1 ha plots, the girth diameter of charcoal producing species was recorded 30 cm off the ground for all individuals with a girth diameter greater than 3 cm. According to our field observations, this was the lower limit of tree harvesting for charcoal production. The tree height was determined using a measuring rod for short trees and a Suunto clinometer for taller trees. Tree species used for charcoal making were identified by the use of a questionnaire (for detailed methods see Kiruki et al., 2017). From this data we derived the expected charcoal harvest potential per ha.

2.3.2. *Initialization of agents*

The household interviews were used to initialise the agent characteristics, based on data that captured the charcoal maker's socio-economic details such as age, cultivated land area, main economic undertakings, motivation towards charcoal making, the quantity of charcoal making and their future plans under varying environmental and policy conditions. All agents belonging to the same typology had similar behaviour patterns although their personal attributes like age and gender varied. The variation in the attributes of the created agents was generated from the variation in the sample of agents interviewed using Monte Carlo techniques (Berger and Schreinemachers, 2006). This method applies the cumulative distribution functions to randomly distribute the attributes of the sample to the created population. Each attribute is allocated independently at the household level thus excluding possible correlations between attributes, generating populations that are robust and statistically consistent with empirical observations. The recreated households were then populated into the study area following the sample distributions.

2.3.3. *Woodland initialization*

The area and location of the woodlands as mapped from the remote sensing data served as the initial data input into the model. The charcoal maker agents were situated within their actual geographic locations, making their interactions with the woodland more representative of the real world.

We used the pantropical biomass model for dry forests (Chave et al., 2005) to estimate the above ground biomass for the charcoal-making species in woodlands (see Kiruki et al., 2017, for more details on woodland data acquisition). This was done by upscaling the biomass from sample plots designated as woodland into per hectare basis. The dry biomass is then multiplied by a charcoal conversion efficiency of 25%, as all the charcoal in the study area is produced via earth mound kilns whose conversion efficiency is between 20 and 30% (Bailis, 2009).

Table 1
Parametrization of model simulation at initialization.

Parameter	Value/numbers	Reference
Households (a) Opportunists	191	Field data and Monte Carlo techniques
(b) Undecided	194	Field data and Monte Carlo techniques
(c) Specialists	140	Field data and Monte Carlo techniques
Household location	Varied	Field GPS locations
Woodland area	23974 ha	2014 Landsat satellite image
Droughts frequency	50%	Mutua et al. (2014)
Household incomes	Varied for each household	Field interviews, using an income accounting approach (Worku et al., 2014; Babulo et al., 2009)
Charcoal value	KSh 450/bag[a]	Field interviews
Charcoal yield	19 bags/ha	Authors calculations based on wood to charcaol conversion rates reported by Malimbwi and Zahabu (2008) and Bailis (2009). Field plots inventory
Woodland regrowth rate	3.3% per annum	Kalaba et al. (2013), Ndegwa et al., 2018

[a] Equivalent to $4.50 (2016).

The resultant biomass is consequently divided by 35 kg (KFS, 2013) to arrive at the charcoal yield per ha in terms of the number of bags. This resultant charcoal yield is used to initialise the model. The recovery time of woodland stands harvested for charcoal are estimated from literature and is assumed to be between 25 and 30 years, which coincides with our field observations in sample plots. This means a growth of at least 3.3% of the total harvestable charcoal wood should be achieved every year if the woodlands were to achieve sustainable production. The initial location of the woodland areas and charcoal makers and assumptions on the parameterization of the model are shown in Supplementary material 1, Appendix 2 and 3 respectively while Supplementary material 2 shows the actual model.

2.4. Scenarios

Table 1 presents the baseline parameterization of the model, which represents the empirical observations of the current situation in the field as realistic as possible. As charcoal production only occurs in the woodland, this is the land cover whose area changes we will be reporting. In the first simulation, we use this parameterization to represent charcoal making under current conditions forming a base scenario. Droughts in the region have been increasing in frequency and severity over the last 20 years (Nicholson, 2016). If this trend continues, households will increasingly depend on charcoal for income. A model scenario with increased drought occurrence (75% probability) is used to show how increased droughts affect the proportion of households in the various agent-types and changes the number of households highly dependent on charcoal for livelihood. The impact of droughts on the woodland is hypothesized to be dependent on charcoal prices, because charcoal prices determine the extent to which charcoal harvesting can make up for lost income during droughts. Therefore, differences in drought probability are tested in combination with different charcoal price levels. To compare if there are any differences on the resulting wood area and number of charcoal makers under normal and high probability of drought, we ran a two tailed *t*-test by comparing the average area and charcoal maker numbers of the 30 simulations for the years 2016–2034 for normal and high probability drought scenarios.

Table 2
Overview of scenarios.

	Droughts probability (%)	Regeneration rate (%)	Charcoal prices (KSh)[a]	Taxation	Yield (bags/ha)
Base scenario	50%	3.3%	450	None	19
Drought scenario	75%	3.3%	450	None	19
Taxation scenario	50%	3.3%	450	Yes	19
	50%	3.3%	562	Yes	19
	75%	3.3%	450	Yes	19
	75%	3.3%	562	Yes	19
Sustainable management scenario	50%	4%	562	None	23

[a] 1 dollar = KSh 100 (2016).

Other scenarios we developed (see Table 2) are aimed to investigate how the introduction of policies by the Kitui county government to regulate and improve charcoal production will change the behaviour of charcoal makers and may favour more sustainable use of woodlands. These policy options include taxation, charcoal price regulation, improved management of woodland regeneration by re-planting and the introduction of more efficient kilns. A kiln is an insulated chamber for wood carbonization. The county government has already taken steps to regulate charcoal production by passing the Kitui County Charcoal Management Act, 2014 which, among others, requires all producers to be organised in registered groups referred to as Charcoal Producer Associations (CPAs) and have designated marketing points. The Act also empowers the County Executive member to regulate marketing of charcoal. This includes empowering charcoal makers to negotiate for better charcoal prices with transporters.

Taxation on charcoal is assumed to reduce the number of charcoal makers and increase production as charcoal makers strive to maintain their incomes. These two effects of taxation have opposing consequences for woodland sustainability and we explored these in a scenario. Based on the survey results, a different probability of withdrawal from charcoal making during the first 2 years after introduction of the tax was assumed for the opportunists (15% probability), undecided (12% probability) and the specialists (35% probability) respectively. A last scenario concerns with measures to more sustainably manage the woodland resources while ensuring that charcoal making continues to be a reliable livelihood option. Charcoal makers usually complain of low charcoal prices offered to them by transporters and this forces them to make more charcoal in order to satisfy their income needs. We, therefore, simulated a scenario where charcoal prices increase. From focus group discussions we gathered that many charcoal makers have information on the benefits of improved charcoal kilns to improve charcoal-yields even though challenges impede adoption. Use of improved kilns will increase charcoal yield and probably reduces the area a charcoal maker needs to achieve the income targets. We, therefore, simulated a scenario where charcoal yields increase by 20% from the current low of 19 bags to a high of 23 bags/ha and higher prices of KSh 562 ($5.60 in 2016) per bag. We assume that charcoal prices will rise by 25% if the charcoal producers are organised to negotiate for better prices. In addition, we assumed a bit higher re-generation rates of woodlands due to better woodland management (reduced grazing pressure) and re-planting of charcoal species (increasing regeneration rate from 3.3 to 4%). Table 2 summarise the various scenarios and parameters under consideration.

2.5. Estimation of uncertainty bands

We estimated uncertainty bands, by taking the average and standard error of 30 simulation runs of the yearly number of charcoal makers and woodland area. The standard error of the yearly number is added and subtracted from the average to give the upper and the lower bounds of the uncertainty band. The uncertainty band for the woodland area and charcoal makers number is presented by plotting the average, the lower and upper bounds of the yearly simulation runs over a 20 year period. The uncertainty band simply shows the extent of dispersion in the simulated data.

2.6. Sensitivity analysis

A sensitivity analysis was done in order to determine the influence of each model parameter on the final number of charcoal makers and woodland area. The aim of conducting a sensitivity analysis is to evaluate how the key model outputs of woodland area and number of charcoal makers respond to small changes in the input components of the model (An et al., 2001; Li et al., 2015). This helps us to identify the most sensitive input components of the model and ascertain the correctness and reliability of the model. In our model, the key model outputs are linked to the input parameters, namely charcoal yield, probability of drought, regrowth rate, charcoal price and probability of agent-type change. We increased and decreased the value of each of these model parameters by 10% and individually analysed their impact on the final number of charcoal makers and woodland area for the year 2035. The final number of charcoal makers and woodland area calculated is an average of 30 simulation runs for the year 2035 based on the different possible variations of input parameters. We consequently calculated the sensitivity index (S_x) using the method of An et al. (2001) and Li et al. (2015):

$$S_X = \left(\frac{d_x}{X}\right)/\left(\frac{d_p}{P}\right) \tag{1}$$

In this equation, X is the value of dependent variable of interest and P is the model parameter value under normal conditions, d_X is the change in the dependent variable caused by the change in the model parameter value imposed (d_P). Higher absolute values of S_X indicates a stronger effect of change on the parameter on the number of charcoal makers and woodland area.

3. Results

3.1. Base scenario results

Under the base scenario, the woodland conversion continues progressively at a rate comparable to rates of woodland degradation over the past decades with a fairly constant number of charcoal makers engaged up to the year 2030. Approximately half of the woodland is harvested for charcoal by the year 2025 and by the year 2030 the entire woodland is harvested (Fig. 4 b&c). As woodland degradation continues faster than woodland regeneration, the distance of woodland resources to the residence of the charcoal producers increases. Hence, soon female charcoal producers cannot find sufficient resources for charcoal making and stop being charcoal producers. This is compensated for by the influx of new charcoal makers leading to stability of the number of charcoal producers (Fig. 4d). After 2030, woodland resources on private lands are becoming scarce making it impossible for opportunists to supplement their incomes with charcoal making leading to a decrease of households engaged in charcoal production. After 2030, the model results in a huge variability in simulated numbers of charcoal makers as shown by the widening uncertainty band (Fig. 4e). The widening uncertainty band is a reflection of declining woodland resource. The declining woodland resource leads to a decrease in the possibility for households to supplement incomes through charcoal production. Different model runs that generate different occurrences of droughts (under the same probability) lead to some differences in outcome. Although the outcome in the final year of simulation is not very different, differences in drought occurrence can lead to slightly different development pathways as drought puts a large pressure on the woodland resources by the need for higher charcoal incomes to compensate for lower agricultural incomes.

3.2. Drought scenario

The total number of charcoal makers went down significantly under high probability of drought from a maximum of 525 individuals at the start of the simulation to a minimum of 238 individuals at the end of the simulation (Fig. 5a). No significant change in charcoal maker numbers was found when the prices of charcoal were at a higher level of KSh 562 and 675 respectively, under similar drought conditions (Supplementary materials 1, Appendix 4). Not surprising, at low price levels and high drought occurrence woodland resources are depleted early, leading to a lower engagement in charcoal making as there are not sufficient resources to be harvested (Fig. 5d). Under this scenario, only 32% of the initial woodland area will be available for charcoal production by the year 2030 and only 11% of the initial woodland area will left by the year 2035. At higher price levels harvested areas are smaller and, hence, even with higher drought probability, resource depletion only occurs towards the end of the simulation period.

The spatial outcomes show that the woodland area declined irrespective of change in price and drought probability. In spite of a smooth average curve over the simulation period for the decline in woodland area, the variation between individual runs is high. This is because droughts occur randomly, thus their frequency and the temporal pattern of occurrence strongly affects the remaining woodland area. In all cases the remaining woodland area is rather small after the 20 year period. However, the differences in the average woodland area under different prices and a normal and high probability of drought were not significant as shown in Table 3.

The different categories of charcoal makers varied widely with changing price and drought probabilities. For all the price levels the number of specialists remained higher throughout the simulation period. Irrespective of the prices, higher drought probabilities generates many specialists as the income gap increases with frequently occurring droughts. The specialists reached a high of 500 individuals when the drought probability was 0.75 and charcoal prices were KSh 562 and 675 respectively (Supplementary materials 1, Appendix 5).

3.3. Taxation scenario

Taxation initially reduces the total number of charcoal makers from 525 to less than 400 for all prices and drought probabilities. This was due to a decrease in engagement in charcoal making as some charcoal producers quit production in the first 2 years upon introduction of taxation. It turns out that this initial decrease of charcoal makers lead to much less variation in the further evolvement of charcoal makers, as compared to the situation without taxation. The number of charcoal makers tends to stabilize with increasing charcoal prices. These results point towards stabilisation of charcoal maker numbers upon taxation. When the drought probability is 0.5 and charcoal prices are at the peak of KSh 675, 53% of the initial woodland area will be available for charcoal production by the year 2030 and only 31% of the initial woodland area will left by the year 2035. However, as the woodland area continues to decline, a further decline in the number of charcoal makers after the simulation period is likely. Fig. 6 below shows the distribution of charcoal makers and woodland area in the taxation scenario.

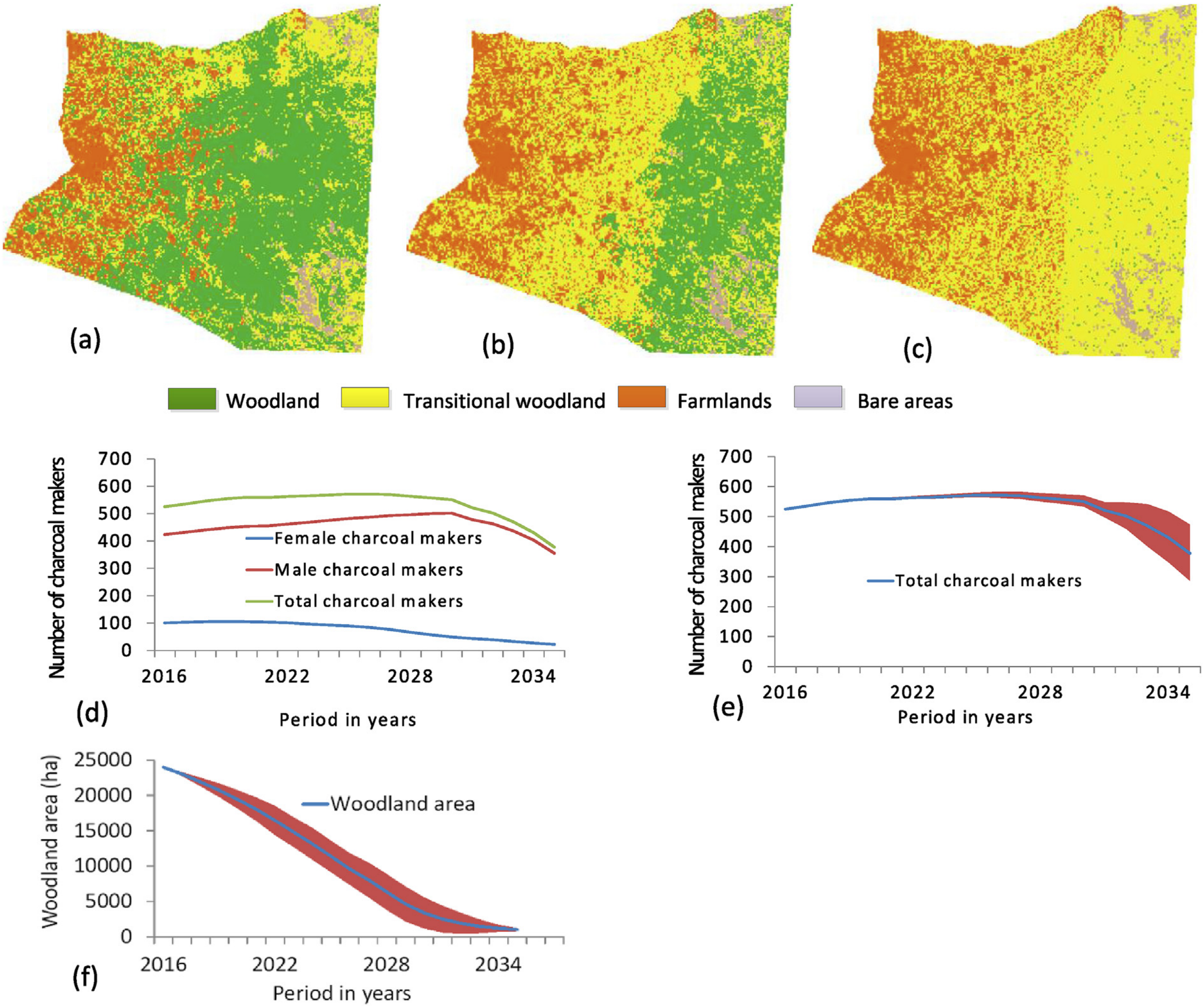

Fig. 4. Woodland cover in the start year 2016 (a) and simulated woodland cover for year 2025 and 2035 respectively (b, c); simulated number of charcoal makers (d), simulated total charcoal makers and associated uncertainty band (e) and simulated woodland area and associated uncertainty band (f) from 2016 to 2035 under the base scenario.

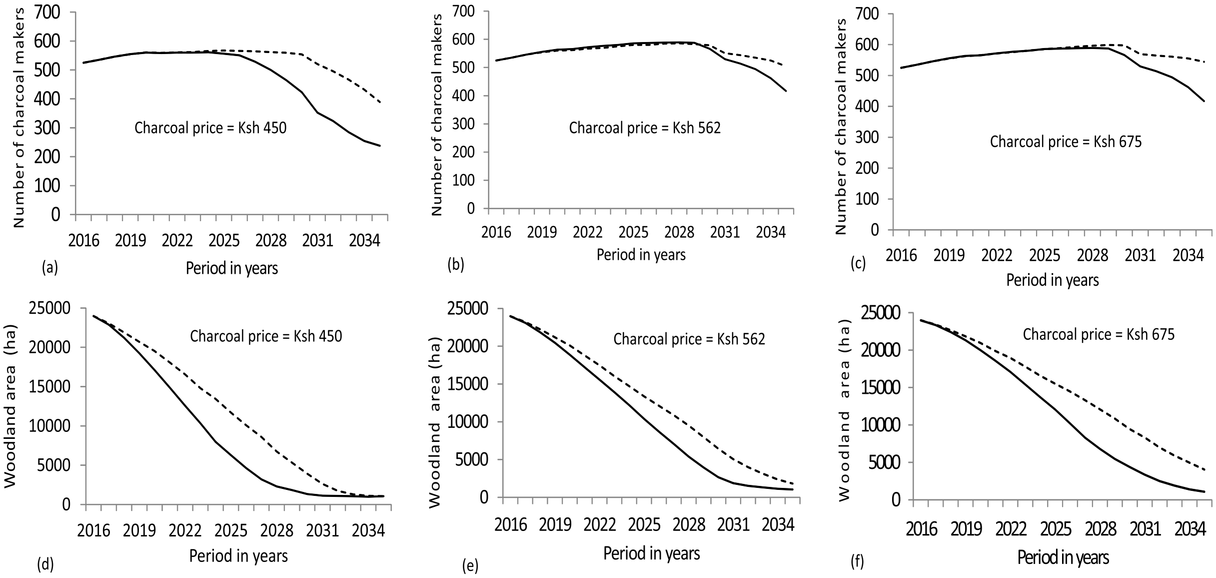

Fig. 5. Simulated number of total charcoal makers (a, b, c) and woodland area available for charcoal making (d, e, f) with charcoal prices of KSh 450, 562, and 675, respectively under different drought occurrence probabilities (dashed line 0.5, solid line 0.75 drought probability).

Table 3
Average woodland area over a 20 year period with varying price and drought conditions.

Charcoal Price	Probability of drought	woodland area	P value	Conclusion
450	0.5	11306	P = 0.33	No significant change
	0.75	8751		
562	0.5	12713	P = 0.40	No significant change
	0.75	10609		
675	0.5	14589	P = 0.21	No significant change
	0.75	11658		

3.4. Sustainable management scenario

In the sustainable management scenario, higher charcoal prices, more regeneration and higher yields are hypothesized to lead to an improvement of the sustainability of the charcoal production. Increased regeneration is due to improved woodland management while higher yields are due to improved kiln efficiencies. Woodland area decreases gradually as the number of charcoal agents increases, hitting a high of 610 agents in the year 2030. Under this scenario, only 55% of the initial woodland area will be available for charcoal production by the year 2030 and only 20% of the initial woodland area will left by the year 2035. The simulated number of charcoal makers will be as high as 575 individuals by the year 2035, which is an increase from the initial number of 525 individuals at the beginning of the simulation period (Supplementary material 1, Appendix 6). With only 20% of the woodland area available for charcoal production, there is a high likelihood of large number of charcoal makers losing their source of livelihood after 2035.

Comparing the woodland area between the sustainable management scenario with the base scenario showed that the sustainable management scenario had more woodland area available for charcoal production as compared to the base scenario (Supplementary material 1, Appendix 6). However, this difference was not significant. This is surprising given the large measures taken that all point towards management with lower resource use and stronger regeneration. The main explanation can be found in the growing number of charcoal makers and higher retention rates as better resource use leads to less depletion, and, hence a higher number of charcoal makers. While in the base scenario charcoal makers have to stop due to lack of resources for charcoal making in their vicinity, this is not the case in the sustainable management scenario. Here the influx of new charcoal makers is accommodated more easily and the higher rate of regeneration even provides a continued resource for female charcoal makers to harvest in the neighbourhood. Nevertheless, also this scenario does not lead to a sustained livelihood on the long term, as the woodland resources do not stabilize but keep declining. In this scenario, as in most of the other scenarios, in the end the specialists become the largest group of charcoal makers putting an extreme pressure on the resources that cannot be compensated for by sustainable management (see Supplementary materials 1, Appendix 7). The difference between the number of charcoal makers in the base and the sustainable management scenario distributions is significant ($P < 0.05$). Under the base scenario, the number women charcoal makers averaged to 73 during the entire simulation period. This number rose to an average of 96 under the sustainable management scenario and the difference was highly significant ($P < 0.05$).

3.5. Sensitivity analysis

Yield and price changes have the greatest influence on the final number of charcoal makers and final woodland area. A negative relationship exists between probability of drought and the assumed probability of changing agent type, suggesting that a larger increase in probability of drought and higher probability of changing agent type would lead to a smaller number of charcoal makers and less woodland area if other conditions were kept unchanged. The number of charcoal makers is especially sensitive to the price and yield of charcoal as well as to the regrowth rate, meaning that increase in these attributes would lead to increased charcoal maker numbers. While the woodland area is sensitive to the price, it is especially sensitive to the probability of change in agent type. Thus an increase in probability of changing agent type (from opportunists to specialists) will lead to reduced woodland area. Table 4 below shows the results of the sensitivity analysis.

4. Discussion

In this study, we have used an agent-based approach to explore the dynamics in number of charcoal makers and woodland over a period of 20 years under varying environmental, social economic and woodland management scenarios. The model acted as a tool to synthesize knowledge obtained from field survey data, focus group discussions, remote sensing and ecological data within a system analysis including feedbacks between the different elements. At the same time, the model allowed exploring the possible consequences of alternative woodland management interventions and an evaluation if alternative woodland management interventions allow charcoal to become a sustainable livelihood resource.

The results generally show a decreasing trend of both charcoal makers and woodland over the modelling period, irrespective of scenario. The findings agree with most literature that report that in sub-Saharan Africa wood resources for woodfuel are declining (Arnold et al., 2006; Ruuska, 2013; Santos et al., 2017). Three factors play a large role in this decline: first, agricultural productivity in the study area has been seriously affected by recurrent droughts as result of declining rainfall (Mosberg and Eriksen, 2015), which has led to more dependence of livelihoods on charcoal (Eriksen et al., 2005). A second factor is population growth, which in the area has led to increased

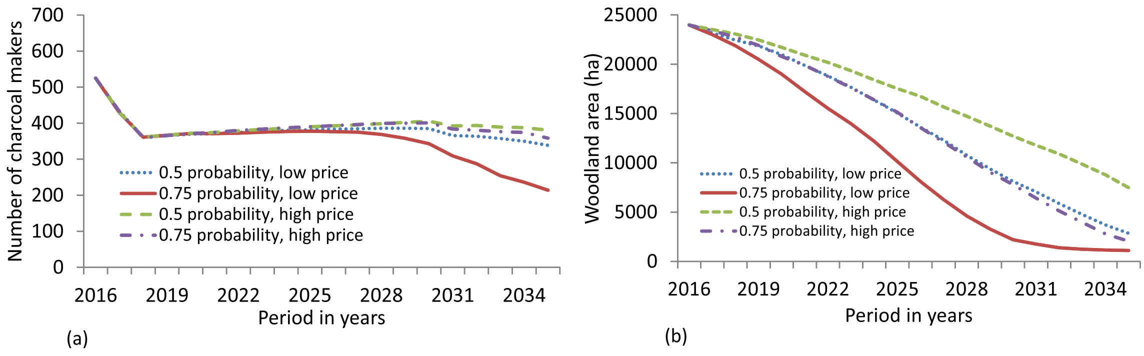

Fig. 6. Simulated numbers of (a) charcoal makers and (b) woodland area for the taxation scenario for high and low charcoal prices and drought probability of 0.5 and 0.75.

Table 4

Sensitivity analysis results of factors affecting the estimates of charcoal makers numbers and woodland area (higher values, higher sensitivity).

Attribute	Sensitivity index (−10%)		Sensitivity index (+10%)	
	No of charcoal makers	Woodland area	No of charcoal makers	Woodland area
Yield	1.245	0.863	1.627	0.2615
Probability of drought	−0.874	−0.822	−0.62	−0.533
Regrowth rate	1.616	1.087	0.85	0.030
Price (KSh)	1.105	0.631	1.136	0.794
Probability of changing agent type	−0.154	0.343	−0.542	−1.448

cultivation, increasing numbers of charcoal makers and other, predominantly extractive, resource utilization methods (Ngugi and Nyariki, 2005). A third factor is related to projected increases in the charcoal market, as it is expected that charcoal demand will continue to rise in sub-Saharan Africa due to rapid urbanization leading to further incentives for participation in charcoal making (Mwampamba et al., 2013; Zulu and Richardson, 2013). The Integrated Model to Assess the Global Environment (IMAGE) estimates that when unsustainable fuel wood harvesting regimes are practised, global forests will be cleared within 30 years as up to 3% of forested area is needed per year to account for the global charcoal demand (Santos et al., 2017). In our case study area, the charcoal production agents operate in an unregulated charcoal production and marketing environment with a lack of alternative livelihoods, which encourages unsustainable wood utilization. Our model shows that the number of charcoal makers, which can be regarded as an indicator of livelihood opportunity, and woodland status are affected by price levels. These price levels depend on the demand/supply dynamics at larger scale. The most striking result of our scenario outcomes, however, is the seemingly inevitable decline of woodland resources. While higher prices and better management reduce woodland degradation in a single year, the positive impacts are counteracted by the possibility for a larger engagement in charcoal making. Consequently, all interventions seem to result in little positive effect on the woodland status on the long term.

4.1. Response to price and drought

Under perfect market conditions, an increase in price is supposed to trigger increased production of charcoal. However, under satisfying conditions and when charcoal production is regarded as hard and risky work, less charcoal is produced as producers meet their income objectives quicker (Jones et al., 2016). Under drought conditions, income from agriculture declines and hence charcoal production increases to cater for the reduced income during such shocks. This is line with other studies where charcoal and other forest products are harvested more to fill the income gap during such occurrences (Felix, 2015; Ndegwa et al., 2016).

The number of charcoal makers increased with a rise in price levels (Supplementary materials 1, Appendix 4). With increased price levels, a charcoal makers can produce less charcoal to meet their income goal. Our results shows that the area of woodland did not respond to changes in drought at any given price level (Table 3). When prices increase, more woodland area will be available for other charcoal makers and the rate of drop out of the system will be much lower. Increased drought probability led to over-reliance on charcoal, consequently leading to a fast depletion of woodlands and subsequent reduction of charcoal makers when they cannot find any wood resource to make charcoal.

4.2. Response to taxation

Taxation of charcoal reduces the income earnings of charcoal makers. Considering that the charcoal makers in our case study are satisficers, it is expected that they will make more charcoal to compensate for the income loss due to taxation. The model implementation of taxation represented concerns that taxing forest products leads to falling returns to labour which may force households with few or poor alternatives to compensate their loss through increased efforts in forest resources utilization, thereby increasing the overall resource use (Anthon et al., 2008). In our study area, this is regarded a realistic assumption as the monetary costs attached to charcoal production are minimal. Other than time and a few simple tools (an axe and a spade) charcoal makers use naturally growing trees either in their farms or in the nearby KSGR which they acquire free of charge or through 'produce and share' arrangements with the land owner. At the same time, there are limits to the scale of production as charcoal making is hard work and with declining woodland resources travel time increases. While this prohibits production beyond filling income gaps, it is not (yet) limiting the production needed to fill the urgent income gaps experienced. The number of charcoal makers declined during the first two years of simulation as producers abandoned charcoal making altogether. Charcoal makers respond to taxation in the first 2 years as it directly disincentives current production practices. It is assumed that by the end of two years, taxation will become a norm and any new entrant will have to factor its cost before venturing into charcoal production. This effect of taxation led to a stabilisation of charcoal producer numbers for the rest of the simulation period (Fig. 6). The anticipated reduction in charcoal makers will probably increase poverty and inequality among the residents as there are limited other livelihood alternatives. Furthermore, while the stabilisation in charcoal maker numbers in the results seems positive, this is unlikely to continue after the end of the simulated period as also under these conditions the woodland resources show a sharp decline. These modelled impacts show that resource conservation and rural livelihood options are intrinsically related and resource conservation strategies such as taxation may not achieve the anticipated impacts. Moreover, there is, given the absence of other livelihood options and the very low livelihood standards little reason to assume that taxation will have an impact through the costs of scale of production. Any variation on specifications of the taxation will lead to impacts similar to what is indicated within the range of scenarios as the mechanism of new incoming charcoal makers and the increasing specialization of charcoal making due to increased drought frequency compensates the positive impacts of taxation. Taxation of charcoal production therefore may fail as a policy/regulatory instrument to reduce the exploitation of forest resources (Namaalwa et al., 2007).

4.3. Response to sustainable management practices

Sustainable charcoal management practices should ensure that the current or increasing numbers of charcoal makers can continue to make a livelihood out of charcoal while ensuring woodland conservation at the same time. Sustainable charcoal production has the potential to enhance livelihood resilience in rural households (Doggart and Meshack, 2017; Elizabeth et al., 2019). In the sustainable management scenario, we assumed all the positive effects of climate change mitigation and improved management are implemented: They include no increased droughts, higher yields, a higher regeneration rate and better prices. While local interventions have little control on drought probability, price increase can happen by improving the charcoal value chain. Mwampamba et al. (2013) estimated that 25–30% of the charcoal value in Kenya is lost through unofficial taxes and bribes, making a price increase for the producers possible upon better value chain management. Regeneration of woodlands can be improved by employing an array of post-harvest management techniques. Such measures include management of coppice, shoot and sucker protection from livestock, managing grazing intensity and protection from fires (Hosier, 1993). All the charcoal in the study area is produced via traditional kilns and adoption of improved kilns can improve production. Improving the management of such traditional kilns, or introducing improved kilns, can result in efficiencies as high as 30–40 percent (and potentially even higher), and less-variable yields (FAO, 2017; Chidumayo and Gumbo, 2013) under the sustainable management scenario.

In our case study area, the number of charcoal makers actually increased during the entire simulation period of this scenario and especially there was a difference in the engagement of woman in charcoal making. This result for women charcoal makers is of great importance to policy makers and planners. According to Butz (2013) income from charcoal production is important to widowed or divorced women and others who are socially and economically marginalised within the society. Production of charcoal and harvesting of other environmental products is among the few livelihood options accessible to the poor, marginalised and vulnerable groups (Shackleton et al., 2008; Adedayo et al., 2010). In Malawi, Smith et al. (2017) observed that in some instances women were more dependent on income from charcoal production than men, as they had fewer alternative income generating options available to them. Many more women can engage in charcoal production and mitigate the effects of poverty when increased management towards woodland regeneration is applied and woodlands near the houses are regenerating in a better manner. Good woodland management strategies can avoid depletion of woodland resources accessible to those groups. However, similar to the other scenarios these positive results are not sustained on the long term. Women charcoal producers, just like other producers, will have to adopt other livelihood strategies in the long run as there is a strong decline of woodland area towards the end of the simulation period. The increase in charcoal makers and extraction upon higher resource availability counteracts the benefits of better management. The carrying capacity of the woodlands is, even upon improved management, insufficient to provide sustained livelihood inputs to such larger groups.

To explore conditions under which the sustainable management scenario would have long-term benefits, we simulated a situation where charcoal makers numbers and ability to change agent type is controlled. We assumed a zero recruitment of new charcoal makers and limited the ability to change agent type in combination with the measures assumed in the sustainable management scenario. We used this approach as restriction of the number of charcoal makers through yearly licencing as well as attaching conditions on the number of bags a licence holder can produce per year constitute the first immediate step towards sustainable management. When these new interventions are implemented, the woodland area declines much slower and only 35% of the woodland area is lost in 20 years (Supplementary material 1, Appendix 8). This is in contrast to the sustainable management scenario where up to 80% of the woodland would be lost if the number and behaviour of charcoal makers is not controlled. By controlling the influx of new charcoal makers, the initial charcoal makers are only reduced by 6% by the year 2030 and only by 11% by the year 2035. This simulation suggests that we can improve on the sustainable management scenario by managing the number of charcoal makers (no influx) and discouraging charcoal makers from becoming specialists. This ensures that charcoal production can only be a supplementary income source for residents and not a major income source. These results also point to the a possibility that woodlands can be managed to provide a source of income for livelihoods for a long period of time, but only to a smaller section of the population. However, at the same time this would mean that a large group of the local population is in need of other livelihood resources. Limiting influx of new charcoal makers and discouraging charcoal makers from becoming specialists will also reduce so-called wood poaching in the KSGR. Some charcoal makers, especially the specialists, illegally produce all their charcoal in the KSGR designated conservation area. This is due to poor enforcement of management rules, as in the current situation only livestock grazing is allowed in the reserve.

In a bid to control charcoal production, the Kenyan government rolled out the forest (charcoal) rules of 2009, which require that producers must get a licence and develop a reforestation plan before being allowed to produce charcoal (KCPH, 2011). After the actualisation of the new constitution in 2010, some counties including Baringo and Kitui developed laws governing charcoal production in woodlands under their control. However, the main challenge is the lack of capacity by the county governments as well as the national government to enforce the regulations. This includes a lack of technical capacity to establish woodland management plans, a lack of coordination and conflicting interests among various government agencies (KFS, 2013). Enforcement of licencing regulations on charcoal harvesting has also been a challenge in other sub-Saharan countries, such as Malawi (Zulu, 2010), Mozambique (Jones et al., 2016) and Burkina Faso (Arevalo, 2016). Development of strong local institutions for woodland management and rigorous enforcement of charcoal regulations along the value chain are suggested as some of the measures which can help manage charcoal production sustainably (Arevalo, 2016). Strong local institutions have been shown to contribute to sustainable management of natural resources (e.g. Gibson et al., 2005; Cronkleton et al., 2011). These institutions define access and conservation rules, resource boundaries and impose penalties and sanctions on abuse (Heltberg, 2001). It has been shown that where local communities undertake collective action and local enforcement of rules, forests and woodlands have a higher probability of regenerating (Chhatre and Agrawal, 2008).

4.4. Model limitations and future improvements

While the model has proved to be a useful tool to understand the interactions between woodland resources and charcoal making in a variable environment, validation is needed to judge the realism of the simulations. However, validation of agent-based models is difficult because of the lack of independent data and the uncertainty in human decision-making and of the socio-economic and bio-physical systems where these decisions take place (Valbuena et al., 2010). Often, this type of models is judged by the plausibility of the simulated results rather than by a validation of the output variables (Sulistyawati et al., 2005; Valbuena et al., 2010). Much simpler models could predict the almost linear decline in woodland area as well and, therefore, formal validation could overestimate model correctness due to equifinality. Moreover, prediction of exact spatial patterns of woodland use are not the main objective of the model.

In our current model, we carried out face validation and qualitative comparison of woodland trends from modelling and remote sensing. Face validation of the model was done to validate the model function against the implemented representation of processes. This involved a structured walk-through checking all the source code. Monitoring of a random charcoal maker and woodland agent over time was also done to see if the characteristics of the agents are updated gradually. The dynamic attributes of the agents are analysed across many iterations of the model and automatic updating of their parameters are checked for consistency and accuracy. Thus, face validation was used to show that processes and outcomes are reasonable and plausible within the frame of theoretic basis and implicit knowledge of the researchers (which was also based on various stakeholder consultations).

A qualitative comparison of resulting woodland change patterns of the simulation was made with the patterns observed through remote sensing over the period 1986–2014 (Kiruki et al., 2016). The simulated woodland change dynamics for the years 2016–2035 resemble the historic patterns with a patchy pattern of harvesting and a gradually shifting frontier of production towards the park boundaries. The trends in woodland conversion in the modelled period are higher than observed over the historic period. To some extent this may be a consequence of the increasing population numbers and increasing occurrence of drought in future situations which increases charcoal production. On the other hand it may point to an overestimation by the model.

Overall, this model is simplified representation of reality and thus may not have captured all the agent decision-making and environmental variables that play a role in the socio-ecological system of the study area. Modelling entails understanding common trends using a simple representation of the real world. (Sun et al., 2016). In our model, we assumed satisficer behaviour for the producers. We also assumed that all producers have the same competency in charcoal production. Firstly, the satisficer approach has been criticized. For example there is no agreed definition of what constitutes a satisfactory result and it is also not clear how such a result differs from the optimal outcome. Another criticism of satisficing behaviour is that it is perceived as a second-best decision based on the premise that a decision maker has reduced his or her aspiration to an attainable level by a ranking of options. It is not clear why the decision maker would go for “good enough” when the very best exists (Harrison and Pelletier, 1997). At the same time, charcoal making is, with the techniques available, hard and dangerous work. Under the extremely poor conditions in the study area agents will need to supplement incomes to survive. Therefore, given the nature of the charcoal production process it is unlikely that agents will tend to produce more than is needed to fulfil these very basic livelihood needs. Secondly, the assumption of similar competency may not be true to across all charcoal makers. Those who are more experienced are likely to use less wood to achieve their desired number of bags than those who are not experienced.

Another limitation of the model is that we assumed zero inflation rates for all goods and services, thus we used constant prices of charcoal over the twenty year period. We therefore assumed that the yearly household income levels would still meet the charcoal makers objectives during the twenty year period. It is possible that changes in inflation rates could lead households to increase their income requirements, hence the need to harvest more charcoal than they are presently harvesting. In general, the current model is mostly designed to explore how the current system functioning will be affected by interventions and a changing climatic context, while more structural changes cannot be accounted for. One of these unaccounted structural factors, is that the present approach to decision-making is based on the assumption that charcoal making is the only fall-back livelihood activity. While this is true for the current situation, circumstances may change over time and new livelihood activities may increase in importance, thus reducing the importance of charcoal income. Also, developments in the energy sector may decrease the demand for charcoal and decrease its importance as a source of income (Kaygusuz, 2012).

5. Conclusion

The agent-based modelling technique applied in this paper has proven to be able to add value to empirical research on the socio-economic and ecological aspects of charcoal making in African woodlands by allowing the exploration of emerging patterns of woodland change and the engagement in charcoal production. By integrating different empirical studies into a model, the simulations made clear that under current conditions of population pressure, a sustainable management for the woodlands in the study area is unlikely to be achieved as the demands for supplementing incomes by charcoal making in drought years exceed the carrying capacity of the woodland system. The exploration of such feedbacks between the ecological and social system influencing the success of potential interventions is essential to avoid failure of interventions. The results indicate that while charcoal provides an input to livelihoods in the area, this is not viable as a long-term strategy. Even under a combination of the stakeholder envisioned interventions woodland degradation continues, and therefore other livelihood options need to be considered to help people deal with climate variability and increasing drought occurrence.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.07.016.

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