Fuel at crossroads

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6.SYNTHESIS

6.1 Introduction

The main objective of this thesis was to understand how livelihood options by local communities were continuously affecting, and are affected by, the extent and composition of a woodland area in a semi-arid area in Kitui, Kenya. Charcoal production is closely linked to livelihoods in many rural areas in sub-Saharan Africa. Charcoal production from forests and woodlands is a major income earner for many households and often provides the important function of being either a safety net during times of emergency or as a gap filler in times of low income (Vollmer et al., 2017). For other households it is their only source of income (Schure et al., 2013; Ndegwa et al., 2016). The extent of charcoal production and period of production is mainly determined by the local circumstances and the reason for production (Jones et al., 2016). Thus, in order to fully understand the charcoal production system and its impacts on the woodlands, understanding what drives the charcoal maker and how they make decisions is vital. At the same time, unsustainable charcoal production may affect the extent and composition of woodland and forests, thus leading to land cover change and affecting the ability to produce charcoal. It may also lead to the loss of a critical source of livelihood for the rural communities.

Holistic research is therefore needed to determine how charcoal production has led to woodland cover and species composition change, the role of charcoal income in rural livelihoods, the influence of charcoal maker's decisions, as well as the role of policy on the spatial, temporal and future state of woodlands. Using satellite imagery, field plot analysis and interviews, we explored land cover change as result of charcoal production in our study area, species composition change, charcoal derived incomes and the various charcoal maker decision strategies under different environmental and policy scenarios. The information from this mixed methods approach was combined in an agent-based model to explore the potential of sustainable woodland management and livelihood options for the study area.

The preceding chapters addressed the following research questions:

1. What are the drivers and extent of woodland cover change in Kitui, Kenya, over the last 20 years and how does the local community perceive these land cover changes?
2. What is the impact of human use of woodland resources, with special focus on charcoal production, on the structure, composition diversity and regeneration of Kitui woodlands over the last 20 years?
3. What is the role of charcoal production on rural livelihoods in terms of income generation, poverty alleviation and income equalization in Kitui, Kenya?
4. What influences the decisions by charcoal makers and how do these decisions affect the spatial, temporal and future state of the woodlands in Kitui, Kenya?
5. How does the implementation of policies influence charcoal maker decisions and sustainable woodland management?

This final chapter gives an overview of the main findings and compares the results with recent literature to evaluate their scientific relevance. The societal relevance of our study is also discussed. We conclude with suggestions for areas of future research based on the remaining open questions and the experiences during the study.

6.2 Overview of findings

Chapter 2 addressed the links between charcoal production, woodland cover change, degradation and how the communities living in the study area perceive these changes. A suite of methods including remote sensing, physical field observations and interviews were used to get an insight in the role of charcoal production on woodland cover change and degradation. We compared woodland loss as captured by remote sensing and compared this with community interviews, followed by an examination of the processes behind the observed changes. Results indicated a strong correlation between land cover change and charcoal-led woodland degradation. There was also a strong correlation between rates of woodland reduction as de-rived from the interviews and remote sensing. More surprisingly, the community feels that their livelihoods have deteriorated despite gaining income from charcoal production. They point at charcoal production and woodland degradation as a trigger of detrimental changes in climate and weather. The combination of methods used in this chapter allows overcoming the limitations of each individual methods of measuring woodland change through a triangulation of evidence.

Chapter 3 investigated how charcoal production impacts on species composition, diversity, structure and regeneration of woodlands in order to help stakeholders undertake viable management measures and maintain sustainable environmental conditions. Results indicated that charcoal producing species have low importance values and account for 87% of the basal area removed for charcoal production. Furthermore, land use is correlated with land cover class, species composition and abundance. This chapter highlighted the need to balance the various land uses in order to ensure sufficient regeneration of woodland species valuable for the livelihood of the local community and maintenance of the ecological integrity.

Chapter 4 focussed on the contribution of charcoal incomes to the livelihoods of local households, grouped by a typology of charcoal household types, and looked at the factors that determine charcoal-making as well as the role of charcoal income in poverty alleviation and income equalization. The achieved understanding on the role of charcoal income among the different household types showed that a multipronged approach is necessary to address sustainable rural livelihoods. Results also indicated that due to the importance of charcoal income in rural households, stakeholders need to explicitly acknowledge its importance and put in place a coherent policy framework to govern the sector.

In Chapter 5 we integrated the data from the preceding chapters and represented the study area as a socio-ecological system, while accounting for the decision-making process of individual charcoal makers, the variation amongst charcoal makers and the adaptation of charcoal making to climatic variation and change in markets and governance. We use an agent-based model (ABM) to simulate woodland cover change and the charcoal maker number dynamics under different environmental and policy options for a period of 20 years. The model experiments showed that female charcoal makers are the first to be affected by woodland degradation. Furthermore, independent of the scenario, the declining woodland resource led to a decreasing number of households depending on charcoal. Controlling the number of new entrants into charcoal production and limiting per capita charcoal production could lead to more sustainable woodland management, as under such scenario only 35% of the woodland will be lost in 20 years as compared to a compete loss of all woodland in any of the alternative scenarios. In general, representing the system as a model that includes the likely future woodland cover and charcoal maker numbers as output can support land managers and policy makers to view the spatial and demographic changes that could occur as a reaction to environmental and policy changes and thus plan for appropriate responses, such as the stimulation of alternative forms of livelihood.

6.2.1 Estimating the effect of charcoal making on land cover change by remote sensing

Land cover change and degradation studies focussing on charcoal and using remote sensing are rare in Sub-Saharan Africa. This is because charcoal making, unlike agriculture, does not lead to complete woodland clearance which can more easily be detected by medium resolution satellite imagery (DeFries et al., 2007). Rather, harvesting for charcoal making occurs in a patchy distribution and occurs at sub pixel level (Oduori et al., 2011). Therefore, accurate mapping of charcoal production areas is only possible with high resolution satellite imagery, but the images required for such studies are often expensive or unavailable for longer time series (Bolognesi et al., 2015). While it was not possible to identify charcoal kilns and trees harvested through our medium resolution Landsat satellite image analysis in our study, spatial patterns and size of degradation patches observed in satellite images together with physical field observations (e.g. of kilns and tree stumps) were found to be reliable in identifying charcoal-related land cover change (this thesis, Chapter 2).

A number of studies have, however, successfully used very high-resolution satellite imagery such as Quickbird and Ikonos to analyse charcoal-related degradation (see e.g. Oduori et al., 2011; Dons et al., 2015; Sedano et al., 2016). These studies used visual interpretation of VHR images to identify changes in tree numbers and kiln sites to estimate the spatial and temporal dynamics of charcoal production (Sedano et al., 2016). Mapping larger areas based on the same method to detect charcoal production is challenging due to costs and time involved. Therefore, specific assessment methods which estimate charcoal production and presence of wood fuel over large areas also have been developed. For example, Bolognesi et al. (2015) developed a rapid semi-automated technique for mapping and estimating the impact of illegal charcoal production in Somalia by setting simple rules for object-based image analysis using worldview-1 imagery. This procedure objectively identified the majority of the charcoal production sites and production areas using minimal labour in visual image interpretation. Basically, it mimics the visual analysis which was applied in Chapter 2 in an automatic procedure.

Although remote sensing is robust and has been successfully used to acquire periodic land cover change and vegetation data over a large areas (Campos et al., 2018) it lacks detailed information on species level. It cannot, for instance, differentiate between sustainably managed stands and those that are completely degraded (Sedano et al., 2016). Therefore, collecting field-based data was vital in our study, in order to differentiate land cover falling under similar classification in remote sensing but with different underlying drivers. In general, field-based data provides indispensable information on the consequences of charcoal production on woodlands and species composition (Aabeyir et al., 2016), which would otherwise be difficult to deduce from remote sensing. Previous studies on wood fuel in SSA have used field plots and satellite image analysis to estimate wood fuel potential of the most important fuelwood species. In these studies, the basal area of these fuelwood species expressed in m^2 was related to NDVI through correlating image pixel values with fuelwood basal area (see e.g. Mutanga and Skidmore, 2004; Castillo-Santiago et al., 2013).Furthermore, linear regression was used to estimate the relationship between field and spectral data of woodlands used for woodfuel production.

Contrarily, in our study species abundance was related to land use/cover gradients because we were mainly interested in the effect of land use, including charcoal making, on population structure Log- linear relationships between stem numbers and diameter sizes showed that farming and high intensity charcoal making had similar effects on tree stem density. This is an example of a difference in underlying cause of land cover change that remote sensing techniques cannot easily differentiate between. Another example that highlights the need to use a combination of satellite and field observations to confirm the actual drivers of land cover change is the role of preferred species within charcoal making. Concentrations of preferred species often lead to increased clearance, which explains the presence of irregular cleared patches deep inside the woodlands in our case study. This explanation is not possible to make with just medium resolution satellite image observations. However, such a patchy pattern is not always present. Chidumayo and Gumbo (2013), for instance, report on charcoal production in woodlands in Mozambique that is characterized by a "clear-felling system" where almost all species are used. In general, the study presented in this thesis overcame the challenge of differentiating land cover falling under similar classification in remote sensing but driven by different causes by using a portfolio of complimentary methods to understand the dynamics and drivers of woodland cover change and degradation at a local scale, a method also used by e.g. Garedew et al. (2009) and Yiran et al. (2012). These methods included satellite image analysis, field plots, field observations and community interviews. A combination of methods enables triangulation and thus limits the shortcoming of individual approaches (Garedew et al., 2009; Kleemann et al., 2017). Interviews, besides remote sensing and field transects, were used to gather richer information, both qualitative and quantitative, on the historical changes in land cover as well as how charcoal production has affected the community's livelihoods. The findings of our study are that (i) charcoal production is among the main drivers of land cover change and (ii) that a portfolio of complimentary methods improves the understanding of dynamics and drivers of woodland cover change.

6.2.2 Effects of charcoal income on local livelihoods and poverty

Recent studies have demonstrated that charcoal income plays a significant role in rural livelihoods in sub-Saharan Africa (e.g. Khundi et al., 2011; Ainembabazi et al., 2013; Ndegwa et al., 2016). However, the potential of charcoal incomes to spur rural development just like other sectors such as agriculture, is often not recognized by policy makers and hence receives little attention in national and sectoral development policies (Smith et al., 2019). This is because charcoal production and trade exists outside the formal markets (World Bank, 2010), which are hard to enumerate. Also, charcoal is often wrongly stigmatized as being an energy source solely used by urban poor (Shackleton and Pandey, 2014). Moreover, the possibility of charcoal production being a poverty trap is rarely addressed. A poverty trap may occur, for example, when low charcoal prices necessitate the need for more production in order to maintain the minimum income level (Belcher and Schreckenberg, 2007). Charcoal production may also turn into a poverty trap through degradation-driven impoverishment (Porro, et al., 2015) or due to a lack of capital accumulation and income diversification in the household (Adam et al., 2013; Wunder and Angelsen, 2003; Campbell et al., 2002).

In general, there is lack of information on the heterogeneity of rural charcoal producers, who vary in regard to their motivation, demographics, production scales, market access, production scales and well-being outcomes (Schure et al., 2013; Jones et al., 2016; Vollmer et al., 2017). In absence of coherent data on charcoal production by rural households, its role within livelihood strategies, poverty alleviation and rural development is likely to be overlooked in policy formulation. This is the case in sub-Saharan Africa where forward-looking policies on the importance of charcoal production as a vehicle for rural development as well as poverty reduction are rare (Sepp, 2008).

Generally, the perceptions of charcoal making communities have not been given prominence in the literature. Most literature focuses on the income benefits of charcoal making to the local communities (see e.g. Schure et al., 2015; Vollmer et al., 2017). An interesting aspect of our study is that the charcoal making community is fully aware of the negative effects of charcoal making on environmental aspects and climate change, despite the monetary benefits (this thesis, Chapter 4). A detailed understanding of the different types of charcoal producers and how the income benefits they receive influences their livelihoods can inspire better policy development (Smith et al., 2017). As currently comprehensive information on rural charcoal producers is lacking, this also impedes the efforts to promote sustainable charcoal production systems (Schure et al., 2013).

Our study contributes to the expanding body of literature which vouches for the potential of charcoal production to contribute to livelihood sustenance and rural development in sub-Saharan Africa (Arnold et al., 2006; Vollmer et al., 2017; Guild and Shackleton, 2018), by 1) highlighting the contribution of charcoal income to the total household income and comparing charcoal income with other income sources, and 2) addressing the community perception on charcoal production. In-depth studies on the role of charcoal income on livelihoods and poverty are rare in sub-Saharan Africa. We are only aware of the studies by

Ndegwa et al. (2016) and Khundi et al.(2011), which focused on the importance of charcoal incomes to various types of producers using cluster analysis and propensity score matching (PSM) methods to ascertain the extent of household welfare attributable to charcoal production respectively. Our study in Kenya has added to this existing literature and further debunked the myth that charcoal production is economically irrelevant (Mwampamba et al., 2013). Charcoal production in our study area contributes to rural development through payment for education and buying of assets such as livestock. Previous field studies in Tanzania and Kenya (such as Hosier, 1993; Ruuska, 2013) have reported that charcoal production leads to woodland degradation, but we are not aware of any previous studies that have tried to explore community perceptions on the effects of charcoal production on the woodland and on their livelihoods. Our study captures the perceptions of a charcoal making community on the negative effects on the environment and livelihoods the first time (this thesis, Chapter 2).

Charcoal on average contributes up to 22% of the household income in our study area. This figure compares well with what is reported in literature for forest based incomes (see e.g. Fisher, 2004; Shackleton et al., 2007; Kamanga et al., 2009; Schure et al., 2013). However, 87% of the charcoal producers in our case study live in poverty (this thesis, Chapter 3), which raises the question on the influence of charcoal income on poverty reduction in woodland areas. The role of forest/woodland incomes on poverty alleviation has divided opinions in the scientific literature. Some authors argue that dependence on forest incomes may turn into a poverty trap through degradation-driven impoverishment (Porro et al., 2015) and lack of capital accumulation and income diversification (Adam, et al., 2013; Wunder and Angelsen, 2003; Campbell et al., 2002). Others argue that forest incomes are important in reducing poverty and income inequality (e.g. Babulo et al., 2009; Khundi et al., 2011; Worku et al., 2014).

Our results show that charcoal proceeds in our case study area are mostly used for subsistence purposes and not for investments in other non-farm sectors. This leads us to believe that the local population is trapped in a charcoal poverty trap. According to poverty dynamics models, households have multiple dynamic welfare equilibria and need a minimum starting level of wealth above the poverty line to escape from poverty. Households which fall below this minimum level of wealth, e.g. due to shocks such as drought or death, will be trapped in poverty unless there are strategies in place to lift households above this critical threshold and safety nets in place to ensure households don't slip back to poverty (Naschold, 2012). To escape poverty, households must move away from low welfare equilibrium to a higher welfare equilibria by making large investments (Enfors and Gordon, 2008). In general, vulnerability to poverty in a woodland system is determined by a number of external and internal dynamics and responses in the woodlands, such as increased droughts and over-exploitation of resources. These factors weaken the adaptive capacity of households and contribute to the persistent nature of poverty traps, therefore calling for increased attention to address them (Tschakert and Shaffer, 2014). For example, the relationship between poverty, asset accumulation and charcoal production needs to be established by longitudinal analysis of livelihood trajectories of charcoal makers (Smith et al., 2019). It has been pointed by several authors (e.g. Arnold and Persson, 2003; Ndegwa et al., 2016) that small-scale producers of forest products may be constrained to make investments in productive assets due to the small incomes they derive and thus cannot invest in capital intensive projects. They also lack incentives and opportunities to invest in more productive activities and have insecure property rights thus perpetuating poverty (Angelsen and Wunder, 2003). Other authors, e.g. Arnold and Perez (2001) and Chidumayo and Gumbo (2013), have argued that better commodity prices for rural producers can actually discourage diversification and hence less resilient livelihoods. By diversifying their livelihood strategies and assets away from the farm sector, rural producers can greatly reduce their dependence on the land and woodland resource and hence reduce poverty. Diversification can act as insurance against risk besides generating extra income and accumulating capital for investments (Barrett et al., 2001). In our case study region, we found that some charcoal makers engage in small business and selling labour as a diversification strategy. However the success of diversification strategies depend on a number factors such as locality, demography, vulnerability and education (Ellis, 1998).

Our results showed that charcoal makers are caught in poverty due to poor environmental conditions, low productivity from kilns and resource depletion. Community members in Kitui list reduction in rainfall, increased soil erosion and wind speed and bee migration as some of the consequences arising from charcoal production. Even though these claims have not been thoroughly investigated, it is clearly visible that environmental degradation has taken place. From empirical data, focus group discussions and interviews, we gathered that droughts affect crop yields and livestock productivity resulting in household impoverishment by reducing income and subsequently increasing the dependence on charcoal. Agricultural productivity in our study area has been seriously affected by recurrent droughts (Mosberg and Eriksen, 2015), which has led to more dependence on charcoal for livelihoods (Eriksen et al., 2005). Increased population growth has increased the number of charcoal makers thus increasing woodland resource extraction (Ngugi and Nyariki, 2005), which has further increased environmental resource degradation. Furthermore, interviews with the community show that the community is aware that charcoal production is gradually destroying their agricultural-based livelihoods and leading them to a poverty trap. For example, to show how charcoal production has led to reduced land productivity and disrupted social systems, in Chapter 2 (this thesis) a community member for instance laments that "*we no longer share gifts, the mwethya (voluntary farmer self-help groups) no longer functions and we no longer visit each other. We wake up early in the morning to search for food and return home late to sleep*". In this context, 'mwethya' groups were used as a source of labour in land preparation. With declining land productivity the 'mwethya' were rendered useless as there is no need to prepare big pieces of land. Declining land productivity meant less food is available to the community.

It is expected that the environmental degradation will eventually feedback into the community's agro-pastoralist lifestyle and negatively impact on the production, thus reinforcing poverty. Our agent-based modelling results (Chapter 5, this thesis) showed that at the current rates of charcoal extraction, the entire woodland area considered will be harvested by 2030 as degradation continues faster than woodland regeneration. This will lead to a decrease in the possibility for households to supplement incomes through charcoal production and will increase poverty and inequality among the residents overall, as there are limited other livelihood alternatives. Other factors mentioned in interviews in our case study area and in the literature that contributed to poverty among charcoal makers include lack of skills, poor charcoal maker health and poor commodity prices offered by charcoal transporters (Oluoko-Odingo, 2009; Kristjanson et al., 2010).

Two key issues that need more attention within studies on charcoal are the physical health of charcoal producers and charcoal pricing within the value chain, as these issues raise serious moral, human rights and fair trade issues. The health consequences of charcoal production on the producers largely remain unknown (Alfaro and Jones, 2018). Charcoal production work is hard, risky and compromises the producers' health and thus denies them the ability to work for long (Jones et al., 2016). Furthermore, charcoal production takes place in remote areas where medical help is hard to find in case of injuries. Moreover, charcoal producers have been reported to suffer physical and emotional abuse by authorities (Zulu and Richardson, 2013). For example charcoal producers in southern Malawi have experienced physical assault in the hands of forest officers. (Smith et al., 2017). In our study area, charcoal producers, especially those operating in the Kitui South Game Reserve, suffer regularly from attacks by armed bandits resulting in loss of property such as newly produced charcoal, work tools and sometimes bodily harm which occasionally leads to death. Health issues may force charcoal producing households to sell their land, livestock or other assets as a coping mechanism, thus sinking further into poverty (Radeny et al., 2012). It is critical to quantify the extent to which the work environment and occupational risks factors of charcoal makers contribute to keep them in poverty.

Furthermore, the informal nature of charcoal trade in sub-Saharan Africa perpetuates poverty, as it is controlled by cartels comprising of transporters, government officials and local elites leaving rural producers with little or no voice. These cartels are powerful, politically connected and therefore dominate all other stakeholders, hampering the formalisation of the charcoal trade as this is not in their interest (Zulu and Richardson, 2013; Neufeldt et al., 2015). This is clearly reflected by what accumulates to different actors in the charcoal value chain. In Kenya and Malawi, studies have for instance reported that charcoal producers receive only 20% of the market price of charcoal (Mwampamba et al., 2013). Growth of urban populations increases demand for charcoal leading to increased distances to the remaining forest resources (Ahrends et al., 2010). Under such circumstances the value chain mainly benefits the urban operators who have financial capacity to collect charcoal from far flung areas and sell it in urban centres (Iiyama et al., 2017).

Most profits accruing for charcoal production are not invested in communities where charcoal making takes place, yet it is these communities which suffer the negative consequences of charcoal production.

For example, in Mozambique just 8% of the profits of licenced charcoal production remain in the charcoal production areas (Baumert et al., 2016). This is also the case in our study area, where producers receive only about 20 – 25% of the sales value per bag of charcoal. Bribes take at least 20–30 percent of the final price (FAO, 2017). A more equitable distribution of benefits along the value chain would ensure better prices for charcoal at the producer level and possibly help to alleviate poverty among charcoal producers. This can be achieved through formalisation of charcoal trade. However, formalisation of charcoal trade should be done with caution as it can lead to unintended consequences. For example it can create new avenues for corruption as happened in Malawi (Zulu, 2010), lead to policy failure and the exclusion and criminalization of small-scale charcoal producers. In addition, it can lead to more environmental destruction as people seek to operate outside policed areas (Putzel et al., 2015). Effective formalisation thus should view small-scale charcoal production as a livelihood strategy which should be nurtured and allowed to flourish rather than archaic or illegal (Spiegel, 2012).

6.2.3 A method for presenting future woodland and livelihood dynamics using agent-based modelling

The work in Chapter 2-4 has shown that charcoal making operates at the interface of human and environmental systems with complex dynamics between household decision making, ecological regeneration and climate variability. Integrating these different aspects can help to understand the speed and dynamics of environmental degradation and generated income. Agent-based models (ABMs) which are computer simulations provide robust tools to represent and analyse complex interactions between humans and the environment (Bah et al., 2006). They can also be used to explore how decision-making processes at the local level eventually lead to land use and land cover change outcomes (Evans and Kelley, 2004). In our study, we have applied a spatially explicit agent-based model to explore the possible impact of changing environmental, economic and policy conditions on the number of charcoal makers and the woodland. Using agent-based modelling in charcoal making studies has never been done before.

Agent-based models allow us to accurately follow and describe emergent properties that result from the interactions between various agents. These properties may not be apparent or are contrary to common expectations (Holm et al., 2018). Therefore, the presented model (this thesis, Chapter 5) can potentially be used to support the design of charcoal making policies in our study area. Thus, in this thesis the model provided both an incentive to synthesize, formalize and quantify insights obtained from the earlier studies (this thesis, Chapters 2-4) into a model, as well as providing a tool to explore the impacts of possible management options. The emergent patterns for both the charcoal maker population and the woodland under different management scenarios form the basis to recommend a woodland management regime which supports the greatest number of charcoal makers while at the same time retaining the greatest area under woodland.

Interpretation of results should, as with any other assessments, be done in the context of the assumptions made. Most importantly, we assume a satisficing behaviour based on our field observations. Unlike the utility maximization behaviour theory which assumes that individuals make rational choices and have access to all information they require, satisficing behaviour assumes that individuals aspire to achieve a predetermined attainable or satisfactory goal. The limitation of using satisficing theory is that there is no single definition of what constitutes a satisfactory result and that it assumes that all charcoal makers have the same competency. However, behaviours may change and it is clear that future conditions will be very different from the current conditions in a context of climate change.

The agent-based modelling outcomes present emergent patterns which can add knowledge to the dynamics of woodfuel resource utilization by giving an insight into issues not observed in the current situation. The first observation is that the resource depletion is taking place at a faster rate than the increase in the number of charcoal makers. Although some uncertain conditions, such as improved agricultural production and management practices such as accelerated regeneration may impact on the exact dynamics, the simulations all point to the issue that after 2035 a big number of charcoal makers will suddenly find themselves with no livelihoods due to resource constraints. The specialists group of charcoal makers will be the charcoal makers that are most affected. At the same time, most of the current woodland will be converted to transitional woodlands which have little value to charcoal production, which increases the risk of poverty if no other livelihood options are accessible in the study area. This highlights the connection between rural poverty and dependence of environmental goods, as people who live in rural and remote areas are much more dependent on environmental goods compared to other sections of the population (USAID, 2005).

However, there are diverse views on the relationship between rural poverty and resource degradation within rural development and sustainable livelihood literature (see e.g. Duraiappah, 1998; Aggrey et al., 2010). One school of thought believes that growing populations affect the finite resource base and thus poverty is seen as a driver of degradation. Following this thought, poverty leads to increased environmental degradation through resource overuse as people try to meet their needs. The degraded environment cannot meet the ever increasing needs of the expanding population thus creating a cycle of persistent poverty (Vosti and Reardon, 1995). Another school of thought is more optimistic and argues that increased population will ultimately lead to lower labour costs which will induce innovations which will in turn improve productivity, promote economic expansion and encourage better natural resource management (Agudelo et al., 2003). Our agent-based modelling results showed a decreasing trend of both charcoal makers and woodland area over the modelling period, irrespective of the scenario. This means more people will sink into poverty and at the same time all the woodlands will be degraded to transitional woodlands. Charcoal making is a major source of off-farm income and its loss will have income and food security implications considering that up to 57% of the charcoal makers spend charcoal income partly on food (this thesis, Chapter 4). Other agent-based modelling studies found that livelihood diversification through off-farm income opportunities such as charcoal production plays a major role in poverty reduction more so under rain-fed agro pastoral systems where climate and price variability are common. The role of off-farm employment is even more important in instances where climate variability leads to seasonal food shortages occasioned by low productivity (Wossen and Berger, 2014).

In our case study, the rapid depletion of charcoal resources is due to a lack of other livelihood alternatives in combination with frequent drought conditions. As we cannot foresee any other livelihood options in the study area in the short term, we believe that this hampers economic expansion and innovation. A study in Ethiopia found that inadequate income due to constrained agricultural livelihood options encouraged overharvesting of fuelwood for sale leading to deforestation and degradation (Amare et al., 2017). In that study, households which engaged in beekeeping harvested smaller quantities of wood in comparison to non-bee keeping households, thus underscoring the importance of alternative livelihood sources in preventing rapid depletion of wood resources (Amare et al., 2017). In conclusion, a high dependency of people on wood from woodlands for generation of income poses serious threats to wood resources (Alelign et al., 2011).

Women are especially at risk of losing charcoal based livelihoods, thus making them more vulnerable to poverty. This is clearly reflected in our agent-based modelling outcomes, as resource depletion leads to early inactivity of women charcoal producers due to lack of woodlands in the neighbourhood. Resource depletion will have serious implications on female-headed charcoal making households, as they do not easily access other alternative productive resources (Quisumbing and Pandolfelli, 2010; Akter et al., 2017). The implications for women losing their forest based incomes are great and diverse, as the income is used buying food, paying for children's education and catering for medical related expenses (Adedayo et al., 2010). Forest and woodland degradation leads to a declining supply of fuelwood and fodder resources and as a result women find it more difficult to meet their subsistence needs. Furthermore, forest degradation may trigger out-migration of male members of a community due to loss of forest resource based job opportunities leaving all farm work to women in addition to their own responsibilities (Jattan, 2003).

Scenarios show that with higher regeneration rates (due to replanting of charcoal species etc.) and improved productivity, it is possible to keep women producers participating for a longer period. Alternatively, in future situations women would need to adapt and move to more distant and dangerous areas in order to produce charcoal. This would present serious challenges to women. First, local norms and values expect women to take care of the children and perform other household chores such as cooking and cleaning. This may prevent women from fully participating in charcoal making in case the wood resources near the home are depleted. Men on the other hand are free to venture further into the woodland in pursuit of tree resources to make charcoal (Wan et al., 2011).

Thus women, unlike men, lack time available for outside labour to perform activities with sufficient intensity for these activities to serve as a principal income earners (Eriksen et al., 2005). Secondly, women operating away from home face a myriad of security challenges as they produce charcoal. Literature reports that women have suffered violence, woodfuel confiscation and a myriad of other abuses in the hands of criminal gangs, forest authorities and land owners (Haile, 1991; Wan et al., 2011).

An emergent feature from our agent-based modelling outcomes, is the relative insensitivity of the woodland cover to different model variables such as charcoal value. In our model, a higher charcoal value will allow more charcoal makers to stay in business. Although higher charcoal prices will allow a lower harvesting per person, it is likely to increase the number of charcoal makers. This is good for livelihoods sustenance, but not for land cover as it does not increase the woodland area as expected. A high price for charcoal is likely to increase the rate of production or harvest and reduce land cover area (Zulu and Richardson, 2013; Smith et al., 2017). For example, in the Sudan, increase in charcoal prices encouraged farmers and herders to begin to exploit forests to produce charcoal for urban markets (Elnagheeb and Bromley, 1994), while in Zambia increased charcoal prices led to clearing of more forests and woodlands (Dlamini et al., 2016). However, in our case higher prices lead to less harvest by individual charcoal makers since they are assumed to be satisficers, but it also means that there are fewer charcoal makers dropping out, leading to more total harvesting. Less harvesting upon higher prices is seen as a reasonable assumption in our case because charcoal making is viewed as hard work (Jones et al., 2016), and producers have little ability to increase production as they mostly work alone.

Another interesting emergent feature of our modelling is found in the sustainable management scenario, where both the number of charcoal makers and the woodland area increased as compared to other scenarios. Increases in charcoal price leads to a reduced need to make more charcoal, while at the same time the assumed reduction of the woodland regeneration time as result of good management boosts supply of charcoal species. This is possibly the best scenario for managing Kitui woodlands, despite the continued resource degradation.

Our method of presenting future woodland and livelihood dynamics using agent-based modelling also has some limitations. First, the random distribution of generated agents could influence the decisions of some charcoal groups and perhaps influence the resulting land cover and charcoal maker populations. Second, in our simulation the woodland patches sprout randomly from transitional woodlands without regard to location. However, in a real world many spatial variables are influenced by neighbourhood characteristics, a condition known as spatial association (Anputhas et al., 2016). For example, charcoal making is more likely to occur near a locality where charcoal production is already existing. Similarly, transitional woodlands near a farmland would have less chances of transitioning to a mature woodland as compared to one in a protected area.

6.3 Relevance for policy development and implementation

Many sub-Saharan African countries lack coherent charcoal policies, which clearly stipulate its role in fulfilling the current and future energy requirement as well as its role in rural development through income generation (Mwampamba et al., 2013). This lack of coherent charcoal policies has handicapped the realisation of the full potential of the charcoal industry, which includes employment creation, an easily available and familiar energy source and a potentially carbon neutral source of energy (Owen et al., 2013). The marginalization of charcoal industry in national energy policies is aided by the long held narrative which links charcoal to deforestation and environmental degradation, and thus a livelihood activity which is hard to integrate with conservation efforts (Bergmann et al., 2017). Lack of information and enabling environment on charcoal production have consequently condemned millions of charcoal based rural livelihoods to illegality and hindered sustainable charcoal production (Smith et al., 2019). With urban based charcoal demand projected to increase, there is need to improve on the sectors sustainability (Mwampamba et al., 2013). To a large extent charcoal making and trade in many sub-Saharan Africa countries exists outside the formal government structures, yet its production has great impact on the land cover and livelihoods of people dependent on it, therefore underscoring the need for studies to inform management and decision making (Sander et al., 2013; Alfaro and Jones, 2018).

Improved understanding of the impacts of charcoal production on land cover change and woodland structure and its role in rural livelihoods and development will help policy makers to shed the negative image of charcoal to a more positive one. Most policy makers doubt the potential of charcoal to contribute tremendously to livelihood and energy needs for sub-Saharan Africa (Neufeldt et al., 2015; Doggart and Meshack, 2017), as most charcoal policies in sub-Saharan Africa are based on misinformation, myths and misconception (Mwampamba et al., 2013). For example, one of the most common myths is that charcoal is a transition fuel whose use will decrease with increased incomes and urbanization as households switch towards cleaner fuels, a phenomenon best described by the energy ladder hypothesis (Leach, 1992). However studies in developing countries have demonstrated that households tend towards fuel stacking and the energy transition does not occur (Nansaior et al., 2011; Van Der Kroon et al., 2013; Choumert-Nkolo et al., 2019).

Many authors (e.g. Mwampamba et al., 2013; Neufeldt et al., 2015) have pointed out the importance of creating sustainable charcoal supply systems, through improved woodland management, assisted regeneration and short rotation plantations. Our observation is that legalization and formalization of charcoal production and trade would clear many of the bottlenecks along the charcoal value chain and guarantee charcoal makers a higher price leading to better livelihoods and reduced poverty levels (Munthali and Murayama, 2015). Formalization of charcoal production has a number of benefits including favourable taxation regimes, collection and investment of charcoal taxes in community and environmental restoration projects and development of tree plantations to meet the increasing urban demand (Schure et al., 2013). Formalisation of charcoal trade in our case would most probably increase the producer prices from the current Ksh 450 per bag to over Ksh 1000 per bag (assuming that all money used in informal taxation is directed to producers), as informal taxation in form of bribes accounts for up to 30% of the value the market value of charcoal in Kenya (Mwampamba et al., 2013). Formalisation would also provide an enabling legal framework that promotes smallholder/private tree-growing for charcoal production (Njenga et al., 2013). Rwanda is a good example of how supportive charcoal policies and an enabling legal framework can support tree growing for charcoal production. With secure land tenure and rising woodfuel prices, farmers have embraced tree growing for charcoal production to the extent that all charcoal is now produced from plated trees on private and community woodlots (Mazimpaka, 2014; Iiyama et al., 2017).

However, the benefits of formalization are more likely to be realized when power and responsibility for woodfuel management are devolved to the local levels, political interference is kept at minimum and the value chain is free from control of powerful urban based actors. For example, it was reported in Malawi that politicians supported illegal charcoal production for political gain. In some instances they even used their influence to press for release of trucks confiscated for violating charcoal harvesting guidelines (Zulu, 2010). Similarly, it has been reported that in Senegal political connections and access to capital can give access to licences and charcoal permits, usually bypassing the local charcoal harvest regulations (Ribot, 2000).

Some studies have found that formalisation can create conditions which are more favourable to urban based charcoal traders at the expense of local producers (Schure et al., 2013). For example formalisation may require producers to acquire harvesting licences from government offices, which may be far away or the cost may be prohibitive for some users. In our case study area, which is characterised by erratic public transport, the nearest forest office is far way (30 km, in Mutomo town). In such a case, urban actors who have the resources and information will have an upper hand over the poor rural producers. Formalisation may also lead to unintended consequences, such as accelerated environmental degradation as producers seek to control the resource being formalised or as they try to beat the guidelines which they find untenable. For example, charcoal producers who are subjected to taxation due to formalisation may feel justified to extract as much charcoal as possible in return. Formalisation may also lead to exclusion, criminalisation and harassment of small scale producers (Spiegel, 2012; Putzel et al., 2015), when they fail to meet the requirements of formalisation. It has been suggested that formation of producer associations may streamline charcoal production and make it sustainable and more inclusive to the small scale producers (Zulu, 2010), as associations will help small scale producers comply with the requirements of formalisation.

The results of our agent-based modelling study (this thesis, Chapter 5) showed that Kitui woodlands can sustain the current levels of charcoal production on the short term, but not in the long-term. Therefore, there is a need for actualizing both short-term and long-term policies on charcoal production. Short-term policies should focus, for example, on improving wood to charcoal conversion efficiencies and enhancing the efficiencies of cooking implements. Long-term charcoal policies should aim at phasing out urban charcoal demand. Such policies should be backed by strategies to encourage more use of 'modern' and 'cleaner' fuels and reduce demand through introduction of fuel-efficient stoves and subsidization of alternative energy forms (Jones et al., 2010). Such a strategy should also include efforts to cushion vulnerable charcoal producing households from income loss through creation of alternative income generating activities (Smith et al., 2019). However this line of thinking has been questioned by some authors (e.g. Mwampamba et al., 2013) who advocate for efforts to promote production end interventions to address impacts of rising charcoal demand. These interventions include, but are not limited to, the introduction of fuelwood plantations, better forest management and assisted forest regeneration.

Specifically for Kenya, despite the availability of necessary policies and legislations for biomass energy development, the policies have not been fully operationalised. The charcoal policy in Kenya is largely defined by the Energy Policy 2000, the Energy Act 2006, the Forest Policy 2005 and the Forest Act 2016. These policies and acts were combined into the Charcoal Policy Handbook 2011, which makes it easier to access all the information on policies and legislation pertaining the charcoal industry from a single source. According to the charcoal policy guidelines, charcoal producers are required to organise themselves into charcoal producer associations whose role is to facilitate sustainable charcoal production. The associations must be registered as an association by the registrar of societies. In our study area, for instance, charcoal producer associations have been formed and registered as required by law, but their attempts to legalise their businesses have been frustrated by the KFS, the local county government and the police, even though these are the very institutions which are responsible for actualising the formalisation of charcoal guidelines. There were also claims that transporters had registered themselves as members of the association, much to the disappointment of genuine charcoal producers. The result is that they gave that association lukewarm support.

Erratic policy pronunciations on charcoal, such as the 2018 charcoal ban in Kenya, have watered down the on-going efforts to formalise and regulate the charcoal trade. These bans show that some policy makers are either still unaware of the current charcoal policy or they do not believe it can be an effective tool to regulate charcoal production and trade. There is also a lack of clarity over which institutions are responsible for particular areas of policy, leading to overlaps and a lack of harmonisation (Wood and Garside, 2014). For example the ministries of energy, agriculture, environment and the KFS are all mandated to ensure sustainable supply of woodfuel, but none of them takes a leading role. This makes implementation, monitoring and enforcing of the charcoal production policy difficult. Poor enforcement means that illegally produced, unsustainable charcoal will continue to be far more attractive than sustainably produced charcoal.

From the results it is clear that charcoal income is an important livelihood option in our case study area that reduces livelihood risks to climate change by providing an income opportunity in dry years. Any economic or policy efforts to regulate charcoal production such as price interventions, production quotas or charcoal production bans must take to account its central role in livelihood sustenance. For example, to be effective, charcoal making bans, such as the one in force in Kitui (which started on February 2018) would need to be complemented with an alternative livelihood option. Experiences from elsewhere show that charcoal bans usually fail. For example in 2006, Tanzania banned all charcoal production and transportation. The aim was to prevent charcoal movement from the source into cities thus forcing charcoal consumers to switch to other alternative sources of fuel. Since charcoal was the most affordable source of energy for most households, its ban led to a huge public outcry. The ban simply drove charcoal production underground, increased corruption and cost of doing business. Due to increased cost of doing business during the ban period, the prices of charcoal doubled. Eventually the charcoal ban was lifted after only two weeks (FAO, 2017). Seeking avenues for active participation of local charcoal producers in sustainable charcoal management is key for both woodland conservation and livelihood enhancement. Local charcoal producers are key stakeholders and decisions about sustainable woodland management strategies must accommodate their views, objectives and perspectives (Mendoza and Prabhu, 2006). This participation must be accompanied by tangible benefits.

The charcoal producing woodlands of Kitui will no longer exist in less than 20 years if the present conditions prevail according to our agent-based model predictions. This will present both ecological and livelihood challenges to a big number of people. Armed with this knowledge and information, the Kitui county government can prioritize managing the woodlands to avert an ecological and livelihood crises. One example would be the formalization of charcoal production in combination with encouraged tree planting for charcoal production. Verified tree planting at farm level could be attached as one of the conditions for association membership and certification can ensure that all charcoal is produced from a sustainable source.

6.4 Limitations and suggestions for future research

Our study faced a number of limitations. First of all, these concerned the data collected. We, for instance, heavily relied on recall data as the small-scale land owners and charcoal producers normally don't keep records. Even though crosschecking of information provided was done, there is always the possibility of under reporting or exaggeration especially on incomes (Dex, 1995; Zhou, 2000). Furthermore, charcoal production has always attracted the 'illegality tag' and many producers may have failed to disclose the full extent of their involvement (Mwesigye et al., 2011; Mosberg and Eriksen, 2015). Besides that, local community members frequently receive government food aid and disclosing their full economic status may disadvantage them as food insecurity is mainly connected to lower incomes (Tingay et al., 2003).

Our study has relied on cross-sectional data for both vegetation and socio-economic studies, missing quantitative data on historical trends. Moreover, we relied on a recall period of one year to get information on incomes. Cross-sectional data has a major limitation as it gives us a snap shot at a time point, making it difficult in uncovering changes over time. This makes it difficult to control for unobserved heterogeneity and fails to detect the true nature, if any, of the relationships investigated (Bowen and Wiersema, 1999; Alem et al., 2014). On the other hand, panel data would have allowed monitoring of the same households and vegetation plots over time and thus would make it possible to identify the time periods when significant changes either in welfare or vegetation status would occur (Zhou, 2000). We, for example, do not know if the degree or intensity of reliance on charcoal has been changing over time.

Establishment of permanent sample plots would also have shed some light on charcoal species depletion over time. While this is an accepted method and widely used in literature, it would be interesting to see results from panel data.

We used agent-based modelling to describe the outcomes of land cover based on environmental conditions and charcoal makers' behaviour. ABMs are appropriate tools for investigating LULC changes because of their ability to represent human decision making processes in a more flexible and context dependent way. However, the complex nature of LULC change processes, coupled with high data requirements and diverse agent making processes makes ABMs best suited for local scale studies (Ren et al., 2019). Data acquisition for use in ABMs is complicated due to great diversity among human agents and landscapes. Individual humans vary in asset endowment, thinking processes and land use behaviours while landscapes vary in terms of land cover, soils and vegetation (Miyasaka et al., 2017). While our agent-based model presents a new frontier on charcoal making research, we used very few variables to calibrate the model due to scarcity of data and a full validation was not possible. Furthermore, we assumed that all charcoal makers are satisficers. In reality, agents may combine satisficer behaviour with more profit maximization style strategies and our assumed behaviours may have been too rigid. More research on addressing other interacting variables can give further insights on charcoal production.

The results from this study reveal a number of interesting knowledge gaps, which need further research. In Chapter 2, community members reveal that despite income from charcoal, they feel that it has destroyed their well-being. If harnessed well, this community perception can be used as an opportunity to vouch for sustainable charcoal production. If the charcoal making community perceives that an initiative for sustainable charcoal production is for their benefit, then they will take actions that will facilitate and sustain the initiative (Bennett, 2016). For example, in Samburu (Kenya) conservationists used the positive perception of the community towards elephants to promote their conservation (Kuriyan, 2010).

Furthermore, research could focus on who really controls the charcoal value chain. Also it would be interesting to assess if the charcoal stakeholders are willing to pay a conservation fee to renew the woodlands and improve the sustainability of the supply chain. Many authors (e.g. Baumert et al., 2016; Kwaku et al., 2018) have advocated for such a fee to be retained at the grassroots level for conservation and sustained management of charcoal resources. However, introduction of such a policy may influence charcoal maker decisions and subsequent sustainable woodland management. For example there are risks that introduction of such a fee to charcoal producers may induce more charcoal production to cater for the added cost or drive charcoal producers further from formal markets to avoid paying the fee.

Charcoal consumption will continue to increase into the future thus calling for more proactive and sustainable production-end strategies, which take possible environmental impacts and the livelihoods of small scale producers who depend on it into account. The question is whether we can identify strategies that balance between the livelihood needs of the people and at the same time minimize environmental impacts associated with charcoal production. Literature has consistently pointed out that most benefits along the value chain do not accrue to producers. Therefore there must be concerted efforts to address value chain challenges (Owen et al., 2013), e.g. replacing the prevailing informal production with economically viable and socially equitable arrangements.