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1. GENERAL INTRODUCTION

1.1 EXTENT AND IMPORTANCE OF WOODLANDS IN SUB-SAHARAN AFRICA

Woodlands are a key vegetation type in sub-Saharan Africa occupying an area of 2.9 million sq. km across 34 countries, representing 23.4% of the total land area (Chidumayo, 2011). Despite their extent in sub-Saharan Africa, woodlands have been less well studied and are poorly understood compared to the tropical rainforest and other biomes (Abbot and Homewood, 1999; Gerhardt and Todd, 2009; Chidumayo and Gumbo, 2010). Woodlands are also poorly addressed by the land use literature because of their broad definition, and therefore often lumped together with dry forests (Timberlake et al., 2010; le Polain de Waroux and Lambin, 2012). Woodlands are defined as any land area with woody vegetation and a tree crown cover of 5-10%, with trees that are able to reach a height of 5 metres at maturity. Woodlands are also defined as any land area with woody vegetation and a tree crown cover greater than 10%, but with trees that are not able to reach a height of 5 metres at maturity (Shvidenko et al., 2005). In comparison, a forest is defined as a land area of more than 0.5 ha with a tree canopy which exceeds 10%, that is not primarily under agriculture or any other non-forest use (Chazdon et al., 2016). It is important to assess woodlands separate from forests because woodlands are more vulnerable to human impacts and the loss of ecosystem services. Secondly, human populations living in woodland areas on average lag far behind to the rest of the world in human wellbeing and development indicators (Uriel et al.,2005).

Woodlands are not only covering a large extent in sub-Saharan Africa, but they are also important for many people: woodlands are, for example, a key source of livelihoods for over 50 million people (Campbell et al., 2000). Woodlands provide a range of goods and services to humans in general and to local rural communities in particular (Pote et al., 2006; Kalema et al., 2015). For instance, woodlands form major grazing and agriculture lands and provide economic income from woodfuel (both firewood and charcoal), timber (building posts) and non-timber products (such as medicines, honey, vegetables etc.). Woodlands also provide ecological services such as soil quality maintenance through protection against erosion and leaching (Feng et al., 2015), regulation of water flows (Uriel et al., 2005; Ryan et al., 2016) and carbon sequestration (Kalema et al., 2015).

In Kenya in particular, woodlands cover approximately 80% of the total land area and are vital for the supply of ecosystem goods and services, livelihood security (e.g. subsistence food production), human settlement and for the local and national economy (Shisanya, 2011). Thirty percent of Kenya's population lives in woodland areas and these areas are particularly important for livestock keeping, woodfuel production and wildlife conservation (Ngugi and Nyariki, 2005; Mganga et al., 2015). For instance, 70% of Kenya's charcoal is produced in woodland areas and these areas also host 90% of the gazetted national parks and game reserves in Kenya (Gachathi and Eriksen, 2011). It is expected that the population dependent on woodland resources will continue to increase due to natural growth and population influx from surrounding areas in search of agricultural land (Shisanya, 2011; Ulrich et al., 2012). The continued pressure on woodlands through subsistence farming, livestock keeping and charcoal harvesting and expected future challenges call for the establishment of viable management measures for the continued wellbeing of communities dependent on these areas, as well as to maintain sustainable environmental conditions and plant diversity.

1.2 DETERMINANTS OF WOODLAND COVER AND USE

1.2.1 Proximate causes and driving forces of woodland change

Human activities in woodlands, just like in other ecosystems, have caused major land use changes as the need to provide food, fibre and shelter has increased over the past decades (Foley et al., 2005). These changes result from complex, non-linear and multi-dimensional processes driven either by proximate causes or underlying driving forces. Proximate causes are the direct changes that take place on the land, while the underlying driving forces are the fundamental processes which are behind these causes. The proximate causes are human-linked activities that directly lead to land cover change. These causes occur at various levels such as households, farms and communities. Examples of proximate causes of woodland change include extensification of agriculture, harvesting of wood and development of infrastructural projects (Ouedraogo, 2010). The underlying driving forces are fundamental social processes that have indirect effects on land use. They include socio-economic factors (e.g. poverty and unemployment), political processes (e.g. legislation), cultural factors (beliefs and attitudes), natural processes (e.g. climate) and technological influences that often interact and act at different spatial scales (Lambin et al., 2001; Sakane et al., 2014; Plieninger et al., 2016; Musakwa and Wang, 2018). Changes in land use or management practices at the local level often have impact on the supply of ecosystem goods and services (Quintas-Soriano et al., 2016). Furthermore, the activities and interactions between individual land users and the land lead to emergent patterns or properties over a wider area. These emergent patterns are properties occurring over a large area and cannot be predicted from observing the micro-units in isolation (Verburg et al., 2004).

While African woodlands have been influenced by both human activities and natural processes over thousands of years, the intensity of human activities has increased significantly over the last century due to increased population pressure, an increase in livestock, infrastructure expansion and rapid urbanization (Chidumayo and Gumbo, 2010; Bouvet et al., 2018). In many woodland areas of Africa, demographic factors, external factors (e.g. urban energy demand), ecological factors and agricultural expansion are the main drivers of land use change (Grogan et al., 2012; Jew et al., 2016). The impact of increased population pressure and subsequent woodland conversion for agriculture, livestock grazing and wood fuel collection has been well documented for African woodlands, as they have led to widespread land use and cover change, species composition changes and environmental degradation. (see e.g. Abbot and Homewood, 1999; Syampungani et al., 2009; Kalema et al., 2015; Lemenih et al., 2014). With ever increasing pressure on woodlands to meet livelihood demands, the challenge is to identify strategic woodland management practices which can guarantee sustainability of the woodlands in the face of increasing demand for forest goods and services in the rapidly changing world (Marunda and Bouda, 2010).

Wood fuel extraction, mainly charcoal production is one of the proximate causes of land use change that has elicited much debate and research in sub-Saharan Africa. (see e.g Butz, 2013; Chidumayo, 2013; Rembold et al., 2013; Sassen et al., 2015). There are still open questions on what drives wood fuel extraction, the extent to which wood fuel extraction leads to land use/cover change, its spatial and temporal dynamics and species composition change.

With demand for charcoal projected to increase over the next few decades in sub-Saharan Africa (FAO, 2017; Mwampamba et al., 2013; Zulu and Richardson, 2013), these questions need to be addressed to in order sustainably manage the wood resources and possibly meet the growing demand.

1.2.2 Woodlands under climate change

Woodlands are influenced by climate change, even though this impact is less evident (Allen et al., 2010). However, increases in mean temperature (about 2–4 ˚C globally), frequency and severity of extreme droughts, heat waves and general drying in some regions are more likely to occur into the future due to climate changes (Allen et al., 2010). In East Africa, it is predicted that climate change will lead to increased rainfall, higher temperatures and a substantial increase in weather variability (Abraha and Gårn, 2016). The risk of extreme weather events such as flooding is also expected to increase (Eriksen and Rosentrater, 2008; Belloumi, 2014). Kenya has experienced generally increasing temperature trends over the last 50 years, combined with a general increase in rainfall events of September to February period. However, the total rainfall has not changed significantly (GoK, 2010).Woodlands are likely to undergo substantial changes in structure and composition in the future as climate change unfolds (Xiaohui, 2016). The environmental impacts of climate change on woodlands include changes on biodiversity, species distributions, home ranges and species shifts. These changes can occur due to changing regimes of precipitation, temperature and carbon dioxide (Bunting et al., 2016). It is believed for example that, woody plants have been encroaching the savannas over the last few decades (Buitenwerf et al., 2012). Increased levels of atmospheric CO_2 may favour vigorous tree growth in woodlands thus increasing their ability to recover from fires and outcompete grasses (Serdeczny et al., 2017). Increased tree growth could, however, make woodlands less suitable for livestock production due to absence of grass. Woodlands may also suffer from increased mortality and other negative aspects (e.g. decreased yield and quality of wood and non-wood products) due to climate driven dynamics of woodland insects and pathogens, as a rise in temperature could extend the ecosystems range of pests and pathogens (Allen et al., 2010). Changing regimes of precipitation and temperature can also directly impact on the woodlands. In the Sahel woodlands for example, a decline in species richness and a 20% reduction in tree density has been reported for second half of the 20th century with reduced rainfall and increases in temperature being the main cause. These changes led to increased aridity and water stress on trees (Gonzalez et al., 2012).

Other than changing woodland dynamics, threats associated with climate change may affect other spheres related to human livelihoods like agriculture, forestry, food security and health (Rahman, 2016). Emerging research from East Africa, for example indicates that that climate change could negatively impact yields of staple crops such as rice, wheat, and maize for the region by roughly 20 percent until 2050 thereby severely impacting agricultural and livelihood dynamics (Olver and Morara, 2018). At the local scale, the changing vegetation dynamics further influence the flow of goods and services which directly affect the people who depend on them (Scheiter and Savadogo, 2016). However, detailed studies on the interaction between climate change elements, livelihoods and land cover change in woodland areas are lacking.

1.2.3 Decision-making at the local level

To better understand the proximate causes on woodland use and cover change, understanding the decision making process by individual land managers is critical. Many individual land managers in agriculture are households whose livelihoods depend on incomes from crop farming and/or livestock keeping. More often these land managers have to contend with challenges and seize the opportunities generated by rapidly changing policy, economic and natural environments in which they operate (Lorent et al., 2008). Previous studies at the household level have shown that land use decisions are generally based on a bundle of factors such land characteristics, ownership, time or season of the year (decisions being undertaken along the land use cycle), expected duration of the decision outcome, nature of the household (e.g. young vs old, men/women headed), demographic composition of the household and socioeconomic status (Singh et al., 2016). Also external factors such as markets, access to market information and institutions influence the opportunities or limitations for particular land use activities (Wyman and Stein, 2010). In general, decision making by households consists of repetitive processes which are constantly adjusted to reflect the socio-ecological environment from which the households operate (Singh et al., 2016). These land use decision making processes have been sufficiently described by behaviour theories drawn from various disciplines such as economics, psychology and sociology. (see e.g. Verburg, 2014; Schlüter et al., 2017; Groeneveld et al., 2017; Sotirov et al., 2017). Decision making theories include for example, the rational choice theory, theory of planned behaviour, reinforcement learning theory, the protection motivation theory, the prospect theory and descriptive norms theory (Meyfroidt, 2013; Keshavarz and Karami, 2016; Schlüter et al., 2017).

Rational choice theory has been an influential theory originating from economics that states that land managers pursue profit maximization objectives only. However this theory has been criticized for being too simplistic, as it assumes that land managers have perfect and complete knowledge and unlimited information processing powers. This theory neither takes into consideration the complexity of human behaviour nor the variation that exists in societies and may result to misleading description of reality (Karali et al., 2011). However, the limitations of this assumption have been acknowledged by combining rational choice theory with the assumption of imperfect information. As a response to the remaining shortcomings of the rational choice theory, the bounded rationality theory was proposed. There are a number of versions of bounded rationality behaviour, depending on the amount and kind of information available and the extent to which cognitive capacity affects decision making (Schlüter et al., 2017). Satisficing behaviour is one of the versions of bounded rationality, which assumes that decision makers have an aspiration level of objectives which they want to achieve and as soon as they find options which meets their aspirational level they stop searching (Groeneveld et al., 2017).

Integrating human behaviour into empirical models which are used in land use studies is a challenge (Irwin and Geoghegan, 2001). A major challenge in the use of behaviour theories in land use studies is the lack of detailed and relevant information on specific aspects of the decision-making processes, so that they can be implemented in a formal model (Schlüter et al., 2017). Households have heterogeneous behaviour and decision making strategies which are not fully captured by behaviour theories hence these aspects cannot be fully included in empirical models. Most empirical techniques cannot capture very precise information about underlying cognitive processes of decision making thus agent-based modelling (ABM) has been developed to address these challenges

(Janssen, 2005). ABM is increasingly used as a tool to capture the nature, rules and motivations behind land use decisions and the external factors influencing those decisions, since ABMs as opposed to other models have the capacity to represent heterogeneous behaviour. In general, ABMs unlike other modelling platforms have the unique ability of combining modelling with other methods of research and can integrate different forms of behaviour theories, as well as micro and macro processes. ABMs can also use spatial and temporal data and blend qualitative and quantitative approaches (Manson and Evans, 2007).

In ABMs, land users are represented as independent decision-making agents, while land is represented as spatial units. Thus by using ABM it is possible to simulate and analyse the interaction between land users and the land, as well as continuous and changing interactions between drivers and feedbacks of land use change (Valbuena et al., 2010b). Due to the ability to include heterogeneity among agents, ABMs 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). ABMs therefore provide a suitable tool to represent human-environment interactions and have become popular in studies on natural resource use modelling (see e.g. An, 2012) and land use behaviour (see e.g. Ligmann-Zielinska, 2009; Valbuena et al., 2010; Brady et al., 2012; Robinson et al., 2012). However, ABMs have yet to be applied to assess the complex interactions between decision making, livelihoods and land cover change in woodland systems.

1.3 SUSTAINABLE CHARCOAL PRODUCTION AND LIVELIHOODS

1.3.1 Charcoal as source of energy for urban areas

Charcoal is one of the main resources from woodlands and plays a major role as a source of energy for millions of people in sub-Saharan Africa. Charcoal is a key fuelwood in many urban areas (Jones et al., 2016), where nearly 80% percent of the population uses it as the main source of energy for cooking (Sedano et al., 2016). Charcoal production has been increasing globally, its production has jumped from 17.3 million tonnes to 53.1 million tonnes over the last 50 years from1964 t0 2014 (Doggart and Meshack, 2017), with mainly sub-Saharan Africa accounting for 62 percent of the entire production. The demand for charcoal has also been rising steadily in sub-Saharan Africa, from an estimated less than 5 million tonnes in 1963 to the current estimate 36 million tonnes in 2015 (Jones et al., 2016; FAO, 2017). This increase is mainly driven by urbanization, population growth and the relative prices of alternative energy sources for cooking and heating (FAO, 2017). Furthermore, the population of SSA is projected to increase two fold from the current 1 billion to 2.1 billion by 2050 (PRB, 2017), resulting in increased urbanisation. The energy needs of the growing urban population will pose an increasing pressure on forest resources of rural areas (Sedano et al., 2016).

Charcoal is preferred to other forms of energy because its relatively cheap, reliable in terms of supply, easier to transport, convenient to use, adds flavour to food and has a clean even burn (Jones et al., 2016). Poor urban households use charcoal as their only cooking energy source while the more affluent households use it among other energy sources. According to the energy ladder hypothesis, households abandon the use of charcoal for liquid petroleum gas (LPG) and electricity as they become wealthier. However, recent research in East Africa has pointed out that households result to multiple fuel use (so-called fuel stacking) as their incomes increases, instead of the linear pattern showing fuel displacement (fuel switching) envisaged at higher income levels (Van Der Kroon et al., 2013; Mwampamba et al., 2013). Most of the charcoal produced in Kenyan woodlands is destined for major urban centres, where it provides energy for 80% of the households (Ruuska, 2013; Ndegwa et al., 2016).

1.3.2 Charcoal as an important non-farm income for rural households

In general, income from charcoal serves as an important source of non-farm income for rural households, with low production investments (Malimbwi and Zahabu, 2008; Butz, 2013; Zulu and Richardson, 2013). Most of the charcoal in sub-Saharan Africa is produced by individual producers using earth mould kilns with conversion efficiencies ranging from 10-30% (Luoga et al., 2000; Bailis, 2009; Jones et al., 2016).

Charcoal production has a positive role in the livelihoods of rural communities through income generation (Mwampamba et al, 2013; Schure et al., 2013; Zulu and Richardson, 2013). Charcoal incomes play different roles within the income portfolio for a wide spectrum of producers ranging from small-scale producers to large-scale operators (Baumert et al., 2016). The income benefits from charcoal are diverse. In some instances the income benefits are huge enough and lift producers out of poverty, which means charcoal production can be a potential pathway out of poverty (Vollmer et al., 2017). One of the poorly understood aspect of charcoal production is the extent to which it benefits individual producers. For example, charcoal making generates income which can be used in agricultural land preparation or cater for pressing needs such as health bills. Some authors argue that these positive benefits of charcoal are in most cases ignored and more emphasis given to negative environmental impacts of the industry (e.g. Smith et al., 2017). Nevertheless, the importance charcoal production on livelihoods is not well understood, especially with regards to its different roles within these livelihoods, varying from being a diversification strategy to a key source of income (Jones et al., 2016). To better understand the importance of charcoal production within rural livelihoods in sub-Saharan Africa, context-specific information on the role of charcoal production for different groups within communities is necessary.

1.3.3. Impact of charcoal on woodland degradation

While charcoal supports many rural livelihoods and contributes to meeting urban energy demands (FAO, 2017), the high and increasing demand is a concern due to possible land cover change and degradation (Zulu and Richardson, 2013). For example, in Kenya, 75% of the charcoal is produced in woodlands (Luvanda et al., 2016), where it is believed to have led to widespread degradation, land cover change, fragmentation and reduction of ecosystem integrity (Hayashi, 1996; Kirubi et al., 2000; Hitimana et al., 2004; KFS, 2013; Ruuska, 2013). The linkage between charcoal production to deforestation and degradation is however under debate (see e.g. Chidumayo and Gumbo, 2013; Coomes and Miltner, 2017). The main point of discussion is whether charcoal production leads to or is a main driver of deforestation/degradation and subsequent land cover change in localities where it is produced across sub-Saharan Africa (Monela et al., 1993), as some authors point out that charcoal production is a by-product of other land uses (Chidumayo and Gumbo, 2013). The ongoing debate on the role and extent of charcoal-driven degradation in woodlands indicates that charcoal led woodland degradation needs to be investigated further (Butz, 2013).

The impact of charcoal production also varies with intensity of production. For example, in areas with a high proportion of preferred species and a high demand the impact on the woodland is much stronger than from production through selective harvesting of trees. However, selective harvesting of trees leads to a reducing tree diversity and causes changes in size class distribution and species composition (Luoga et al., 2002; Hitimana et al., 2004). Furthermore, the effect of charcoal production on long-term vegetation structure and tree species diversity is not well understood (Wurster, 2009). Charcoal production may also lead to other environmental impacts such as wind and water erosion due to soil exposure and increased runoff and changes in catchment hydrology due to tree cover removal (Santos et al., 2017). To promote sustainable use and safeguard the health of dry woodlands, information about composition, diversity, structure and regeneration of plant species in dry woodlands are of great management and conservation importance. This is particularly the case in absence of formalized and sustainable wood harvesting guidelines (Doggart and Meshack, 2017).

Sustainable production and use of charcoal is recommended in the literature as a way of averting ecological and environmental consequences of charcoal production (Khundi et al., 2011; Njenga et al., 2013). The recommendations range from supply chain improvement (Baumert et al., 2016) to sustainable woodland management (Wessels et al., 2013; Ndegwa and Anhuf, 2018), market formalisation (Neufeldt et al., 2015) and safeguarding resource access and land tenure security (Chidumayo and Gumbo, 2013). The recommendations, however, often lack a good context-specific underpinning of the dynamics of woodland resource use and are, therefore, often difficult to implement. For example, none of these studies have incorporated the aspect of human decision making, to understand what drives charcoal making. In the absence of such information, implementing sustainable charcoal production may be difficult or even counterproductive. For example a case study in Lijiang County, northwest Yunnan province of China showed that charcoal making and deforestation was largely driven by resentment towards authorities and lack of economic opportunity relative to other members of society and not necessarily poverty (Zackey, 2007).

1.3.4 Way forward on modelling decision-making within the charcoal system

Charcoal production is an important income generation activity in sub-Saharan Africa (see e.g. Jones et al., 2016; Ndegwa et al., 2016; Smith et al., 2017). Engaging in charcoal production is an individual decision as each charcoal maker strives to meet their objectives after considering a host of land use options available to them. Charcoal makers decisions have obvious consequences for the woodland while the decisions the charcoal makers make are influenced by the performance and characteristics of the biophysical components. Due to the complexity of human decision making behaviour and multiple interactions between woodland and socio-economic components, appropriate models which can capture such complexity are needed. ABM is an appropriate tool as it allows for modelling biophysical and social-economic components of the woodland system and the feedbacks between them. The charcoal production system is a complex socioecological system involving the interactions between the biophysical components (woodland and their products) and the socio-economic components (demographic, behavioural and economic aspects of charcoal makers). Human decision-making at the local level links the biophysical and socio-economic components of a socioecological system together (Haggith et al., 2003). In this thesis we model this link using ABM.

1.4 DESCRIPTION OF THE STUDY AREA

The fieldwork for this thesis was conducted in Kitui County in South Eastern Kenya, which is classified as an arid and semi-arid area. It covers an area of 30.570 km^2 and is considered one of the largest counties in Kenya. The county lies between an altitude of 400m and 1800m above sea level and receives an annual precipitation of between 300mm-1050 mm. These rains are usually erratic and unreliable. Subsistence agriculture is the mainstay of the county and 66% of the population lives below poverty line (Ndegwa et al., 2016). The major environmental issues are land degradation due to soil erosion and forest degradation. Forest degradation is mainly driven by wood extraction for domestic use and charcoal production to raise incomes (KCDP, 2013).

The study presented in this thesis was carried out in a case study area of 442 km^2 in the southern part of Kitui County (see Figure 1.1). We have chosen the study area as it shows a lot of critical issues related to woodland management found across large areas of woodlands in sub-Saharan Africa, namely uncontrolled charcoal making and the resulting environmental degradation, high poverty rates, high population growth rates and unpredictable weather conditions. The case study area is also located at the interface between private and public woodlands, thus giving researchers an opportunity to investigate the charcoal production dynamics of those two land use systems. The fieldwork for this thesis was carried out between May 2015 and June 2016.

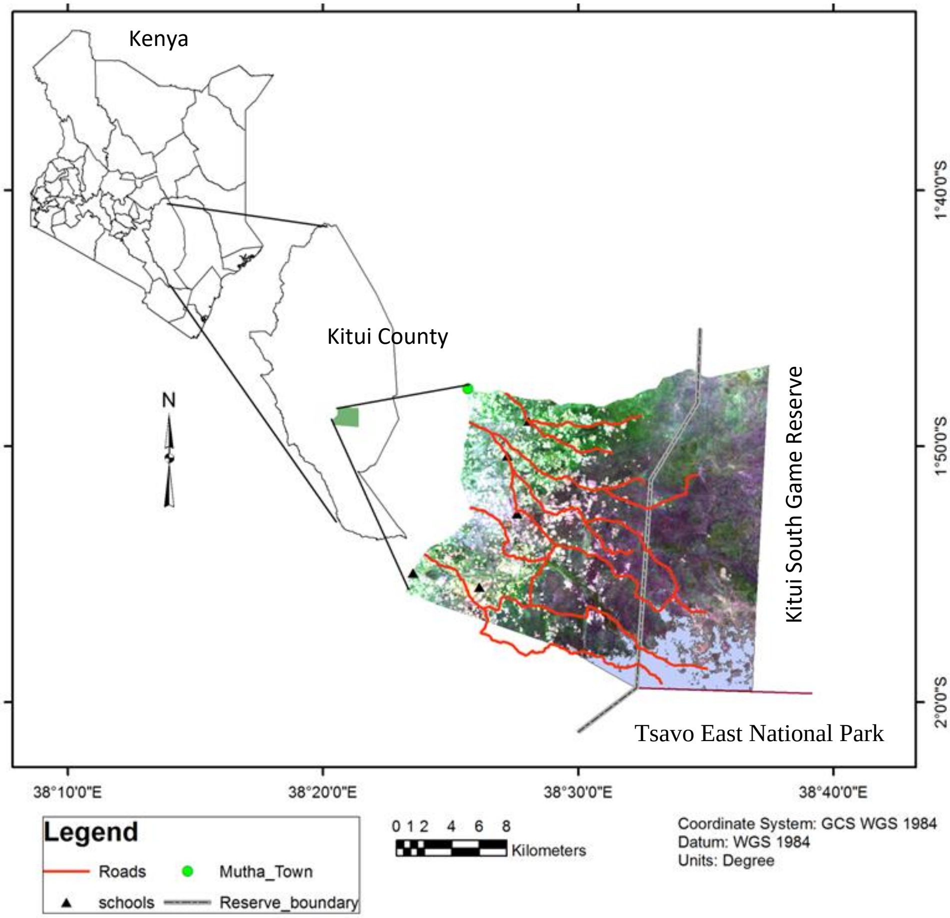

Figure 1.1 Location of study area within Kenya.

1.5 GOAL OF THIS THESIS

The overarching objective of this thesis is to understand how livelihood options by local communities are continuously affecting, and are affected by, the extent and composition of a woodland area in a semi-arid area in Kitui, Kenya. We seek to enhance our understanding of woodland degradation and to assess the role of charcoal making in woodland degradation by using a portfolio of methods in order to propose sustainable woodland management options. Moreover, we aim to understand the impact of different land use activities such as charcoal production on four dimensions of woodland, namely species composition, woodland structure, woody biomass distributions and regeneration. Furthermore, the role of charcoal making on the livelihoods of the communities living in the case study area are assessed.

Finally, we hope to achieve a better insight into the future distribution of the woodland by combining their spatial and temporal patterns with local decision making by means of an agent-based modelling (ABM) approach. Specifically, we are interested in understanding the motivations underlying human decision making with respect to woodland resource utilisation through charcoal making. We aim to understand how these decisions interact with the ecology of the woodlands, providing insight into the possible future of these woodlands.

We believe that such an approach will help us to gain insight into the complex interrelationship between the objectives of land users, current policy incentives and livelihood options. Using an ABM approach also allows us to assess the effect of potential future policy interventions, as it is a useful approach for evaluating alternative interventions to achieve sustainable management of the woodlands. Therefore, interpretation of the different elements of the thesis will be made in terms of the implications for sustainable management of these woodlands.

The broad objective of this thesis is achieved by addressing four complementary 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 potential implementation of policies influence charcoal maker decisions and sustainable woodland management?

1.6 SET UP OF THE THESIS

This thesis consists of four main chapters and each addresses one of the interrelated research questions set out in section 1.5, concluding with an overall synthesis in Chapter 6. Figure 1.2 shows the structure and sequencing of the thesis chapters.

In Chapter 2, we reconstruct land cover change history and woodland degradation in the study area based on the interpretation of satellite imagery, field-based charcoal site identification and interviews with local land- owners. The aim is to determine the rates of woodland cover loss, the role of charcoal making in woodland cover change and how these land cover changes affect the livelihoods of the local community. Ultimately we provide a method of linking woodland degradation, charcoal making and perceived change to livelihoods for the local community (Research question 1).

In Chapter 3, we investigate, through an in-depth field survey, the impact of different land use activities on four dimensions of woodland, namely species composition, woodland structure, woody biomass and regeneration. This is determined by use of field plots, as it acknowledged that human activities such as wood harvesting and land use can reduce or eliminate biomass of trees and shrubs, thereby altering their ability to provide ecological and economic services such as charcoal provision. Such information can best be captured at the plot level and the collected information is used to answer Research question 2.

In Chapter 4, we clarify the role of charcoal on livelihoods of the community living in the study area. Through in-depth interviews with charcoal makers, we were able to construct 3 typologies of charcoal makers that capture charcoal-making motivation and the extent to which they depend on charcoal income. This formed the basis to understanding the importance of charcoal income on poverty mitigation and income equalisation as well as the determinants of likely participation in charcoal making (Research question 3).

In Chapter 5, we developed an agent-based model that captures the interactions between the woodland system and the decision making of charcoal makers in the case study area. This model is used as both a boundary object for integration and a tool to help understand the outcomes of interactions. By using data from field interviews and potential external policies, we were able to simulate several scenarios that provide insight in local livelihood and woodland dynamics as well as charcoal maker decisions and sustainable woodland management options for the next 20 years (Research question 4 and 5).

In Chapter 6, the methods and results from Chapter 2-5 are discussed in the context of sustainable woodland management possibilities for the case study area. Furthermore, the academic and societal relevance of the study is highlighted.

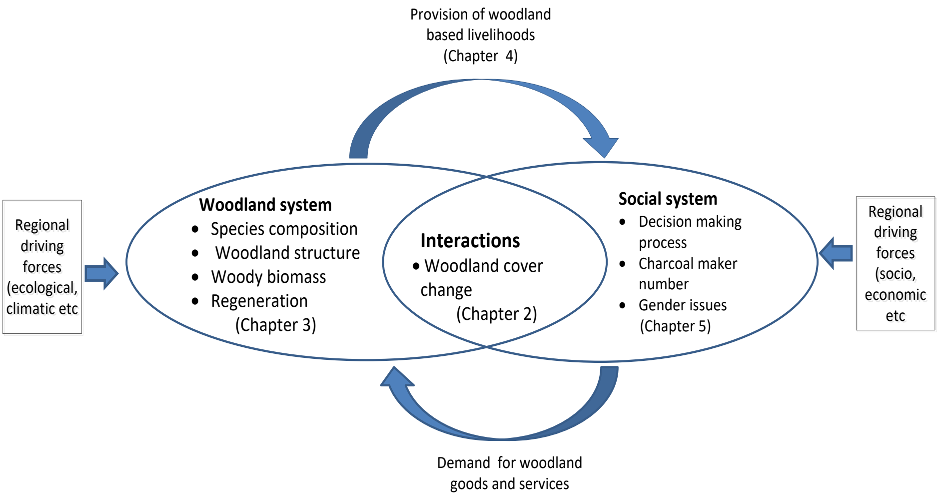

Figure 1.2 Schematic display of chapters 2-5 in this thesis. The arrows indicates an information flow between the chapters.