Causes and consequences of fire in the miombo woodlands of south-eastern Tanzania

THE UNIVERSITY of EDINBURGH

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Declaration

I declare that this thesis has been composed by myself and that the work has not been submitted for any other degree or professional qualification. I confirm that the work submitted is my own, except where otherwise acknowledged in the relevant chapters. One of the chapters of this thesis has been published, with details summarised below.

Ellie Wood, 2022

Chapter 4. Intentions behind common and risky fires in south-eastern Tanzania

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Author contributions: EW designed the data collection, with inputs from CMR, KS, JAF and IG. EW and MM collected the social data; EW led the thematic analysis with inputs from MM and KS. CA led the remote sensing analysis with inputs from EW and CMR. EW led the writing of the manuscript; all other authors reviewed the manuscript and suggested improvements.

Abstract

Disturbances such as fire and herbivory maintain the open tree canopies and grassy understoreys characteristic of southern African miombo woodlands. However, recent loss of woodland cover across the region via degradation threatens the future of these ecosystems and some of the services they provide to people. Understanding the causes and impacts of degradation is therefore a prerequisite to sustainable management of miombo woodlands. In this thesis I present a case study of Kilwa District, south-eastern Tanzania, to explore degradation at multiple scales, with a particular focus on fire. Fire in miombo woodlands has both detrimental and beneficial impacts – via complex effects on ecosystem structure, carbon emissions, local hazards and livelihoods. While fire is often assumed to be a major cause of degradation in inhabited landscapes, the empirical basis for this is weak and research exploring fire causes and impacts remains limited outside of protected areas. In this thesis I aim to assess causes and consequences of fire, their synergies and trade-offs, through three empirical research chapters. I ask: does fire drive degradation? What are the causes of fire? What are the impacts of fire on local peoples' wellbeing?

In the first research chapter I establish tree demographic rates across Kilwa District and explore variables related to tree growth and mortality, based on the resurvey of a network of woodland plots consisting of ~1700 stems at 12 locations. Data were collected on large diameter (≥40 cm diameter at breast height) stems because large trees are keystone structures in miombo ecosystems with strong influences over biodiversity and carbon storage, but long-term studies exploring their demographics and potential threats have not been undertaken. I find that aboveground carbon storage and diversity of large trees remained stable over a period of nine years. Mortality was offset by stem growth and recruitment. Results from modelling and focus group discussions suggest that wounding, over-harvesting, and fire represent constraints on growth and/or survival of large diameter stems. Fire was not associated with increased mortality, but reduced growth rates of large trees. The evidence presented here shows that the current fire regime is not driving degradation in Kilwa, challenging prevalent narratives.

In the second research chapter, I explore human aspects of use and misuse of fire, including the motivations behind fire use and the extent to which human intentions drive the fire regime. Using data from interviews and focus group discussions in farming communities in combination with remote sensing, I identify intentions behind fire use and the perceived relative frequency and riskiness of fires set for different purposes. I found that the most common ignitions were intentional and important to livelihoods and that burning was optimised for the intended outcome. The largest land area burned during the late dry season when people burned for activities such as field preparation, and when environmental conditions encouraged fire spread. These findings offer an insight into how positive intentions shape the fire regime at the landscape scale.

The final research chapter focuses on the consequences of fire for local people. I used the capability approach to analyse, for the first time, fire impacts on multiple dimensions of wellbeing. I found that both controlled and uncontrolled fires were a means for improving wellbeing, particularly when used as a tool with a specific purpose. Fire was also a negative wellbeing converter, principally as a hazard unrelated to the original purpose, when it became uncontrollable. Most respondents considered these hazards as sometimes-unavoidable risks related to activities necessary to achieving broader wellbeing goals. Respondents reported that freedom and choice is a crucial component of wellbeing, supporting calls for integrated fire management which does not undermine the agency of those who inhabit fire-prone ecosystems, and who depend on their environment to improve their own wellbeing.

Lay summary

Miombo woodlands span 2.7 million km^2 across southern Africa. They harbour rich natural diversity, and are globally-important stores of carbon, helping to mitigate climate change. Miombo woodlands also provide benefits to millions of rural people who live in them and are known as 'social' woodlands because of the significant interactions between people and nature there. For example, 'bushfires' or 'wildfires' have burned in miombo woodlands for thousands of years, and many species in the miombo are adapted to the presence of fire. Most fires are started by people – who burn for many activities, such as preparing fields for farming, to aid in hunting, or to ward off dangerous animals. Fire has long been of interest to land managers and researchers because of its potential impacts on woodlands. Evidence from experiments shows that if there is 'too much' fire, woodlands can be converted to grasslands, threatening many of the benefits they provide to people. However, much of what we know about fires comes from experiments and studies in protected areas. Very little research has been conducted on the causes and consequences of fires in places inhabited by people.

In this thesis I aim to identify causes and consequences of fire in inhabited miombo woodlands. I present research on both environmental and social aspects of fire at my case study site: the Kilwa District of south-eastern Tanzania. First, I explore whether the current fire regime (the timing and patterns of fire) is threatening benefits provided by trees. I analysed data from two woodland surveys conducted in 2010/11 and 2019. I found that fire slowed the growth rates of individual trees, but it did not increase the odds of trees dying. Tree diversity and carbon storage did not change between surveys. This provides evidence that the current fire regime is not causing a loss of tree cover in Kilwa District.

Secondly, I used interview data from six study villages to identify the main causes of fire. I analysed this in combination with data from remotely sensed maps of burned land area, to explore how human intentions drove the fire regime. I found that the most common ignitions were intentional and important to many local livelihood activities such as farming and keeping livestock. The largest land area burned during the late dry season (from July until November) when people burned for several activities, and when environmental conditions encouraged fire spread. People set fires in specific ways to meet their aims: for example, burning in hot and windy conditions if they wished fire to spread far. This highlights the important uses of fires for local people and shows that many aspects of the fire regime are intended by local people.

Finally, I used interview data from six study villages to identify the good and bad impacts of fire on local people. I first identified a range of factors considered important to local wellbeing. Then, I identified the positive and negative ways that fire can influence wellbeing goals. I found that both controlled and uncontrolled fires could improve wellbeing, particularly when used as a tool with a specific purpose. Fire was more likely to negatively impact wellbeing when it became uncontrollable and hazardous, with these impacts usually being unrelated to the original aim of the person who set the fire. However, most people were accepting of these hazardous risks because they were considered a side-effect of activities like farming, which were important to wellbeing goals. These findings point to the helpful and harmful consequences of fire for people, which must be considered by land managers aiming to manage fires for social and environmental benefits.

I then discuss the implications of these findings. I identify several trade-offs related to fire as indicated by the research presented here, such as the important uses of fire in livelihood activities versus potential hazardous side-effects when fires are uncontrollable. However, I also highlight that the current fire regime is largely successfully managed by local people, as it maintains important livelihood activities, without posing a threat to miombo trees. I conclude that formal fire management carried out in or near places inhabited by people must include and engage with those people, to ensure positive outcomes for humans and the environment. I recommend ways this kind of fire management could be applied in Kilwa, based on the findings of my research.

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I wish I could blame the typos in this thesis on cat paws on my keyboard, but any mistakes were made by me. Everyone else involved made it better.

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"We… have to go beyond the role of human beings specifically as 'consumers' or as 'people with needs', and consider, more broadly, their general role as agents of change who can — given the opportunity — think, assess, evaluate, resolve, inspire, agitate, and, through these means, reshape the world"

Amartya Sen, 2013

Chapter 1. Introduction

Uncontrollable fire in Likawage village, Kilwa District, Tanzania (Ellie Wood, 2019).

Chapter 1. Introduction

1.1 Relevance of this thesis: the need to reconcile international social and environmental goals

Sustainable environmental management underpins the wellbeing of current and future generations (Holland, 2008; Dearing et al., 2014; Steffen et al., 2015). Decades of research establishing that a large proportion of the world's ecosystems are in a crisis state have triggered the development of major international goals such as the Sustainable Development Goals, and the aim of The UN Decade on Ecosystem Restoration: to prevent, halt and reverse ecosystem degradation. However, trade-offs between ecosystem services present major challenges to meeting those goals (Howe et al., 2014; Mace et al., 2018). While the scale of the challenge is global, many trade-offs, such as between achieving poverty alleviation, improved management of terrestrial ecosystems and climate change mitigation, exist at landscape and community levels and can only be understood via empirical evidence obtained at those scales (Fisher et al., 2014; Cavendar-Bares et al., 2015).

In response to the environmental crisis, there is an enormous global drive to reduce deforestation and forest degradation in order to mitigate climate change and limit biodiversity loss (e.g. Houghton, 2013; Corbera & Schroeder, 2011; Gibson et al., 2011; Luyssaert et al., 2008). However, the landscape-level realities of the relationship between tree cover, carbon storage and biodiversity are complex (Paoli et al., 2010; Veldman, 2016; Veldman et al., 2019). Additionally, land management focused solely on these goals can lead to local policies that don't align with, or undermine, traditional land management practices and can have a negative impact on local livelihoods and wellbeing (West et al., 2006; Larson et al., 2018). This thesis intends to address one aspect of this complex and urgent set of issues by exploring the role of fire, which is widely cited as a cause of woodland and forest degradation, its causes and impacts on people and trees in Tanzanian miombo woodlands.

1.2 Geographic context: the 'social' miombo woodlands of southern Africa

Southern African landscapes are dominated by savanna woodlands consisting of grassy understoreys and open tree canopies. Historically, these ecosystems have shaped and been shaped by human communities (Frost, 1996; Chidumayo, 1997; Comberti et al., 2015). Today, these 'social' woodlands of southern Africa continue to provide global benefits through carbon storage and biodiversity, and local benefits supporting the livelihoods of 100 million rural and 50 million urban residents (Ryan et al., 2016). In turn, people impact the structure and functioning of southern African woodlands through subsistence and commercial activities such as agriculture, charcoal production, building and repairing homes, resource collection, and urbanisation: activities which may be amplified or suppressed by land governance (Ahrends et al., 2010; Jew et al., 2016; Woollen et al., 2016; Nunan et al., 2018).

Miombo woodlands, defined by the dominance of the genera *Brachystegia*, *Julbernardia* and/or *Isoberlinia*, are the most extensive of the southern African savanna woodlands, distributed 2.7 million km^2 across Angola, DRC, Zambia, Zimbabwe, Malawi, Mozambique and Tanzania (Figure 1.1). Miombo countries have a combined, mostly rural, population of 247 million (Ribeiro et al., 2020b). Typically found on nutrient-poor soils, miombo woodlands are semi-deciduous and broad-leaved, with low specific diversity. Most tree species belong to the Fabaceae family (also known as the Leguminosae family) and Detarioideae subfamily (Ribeiro et al., 2020c), with species composition varying between regions (Morris, 1970; White, 1983).

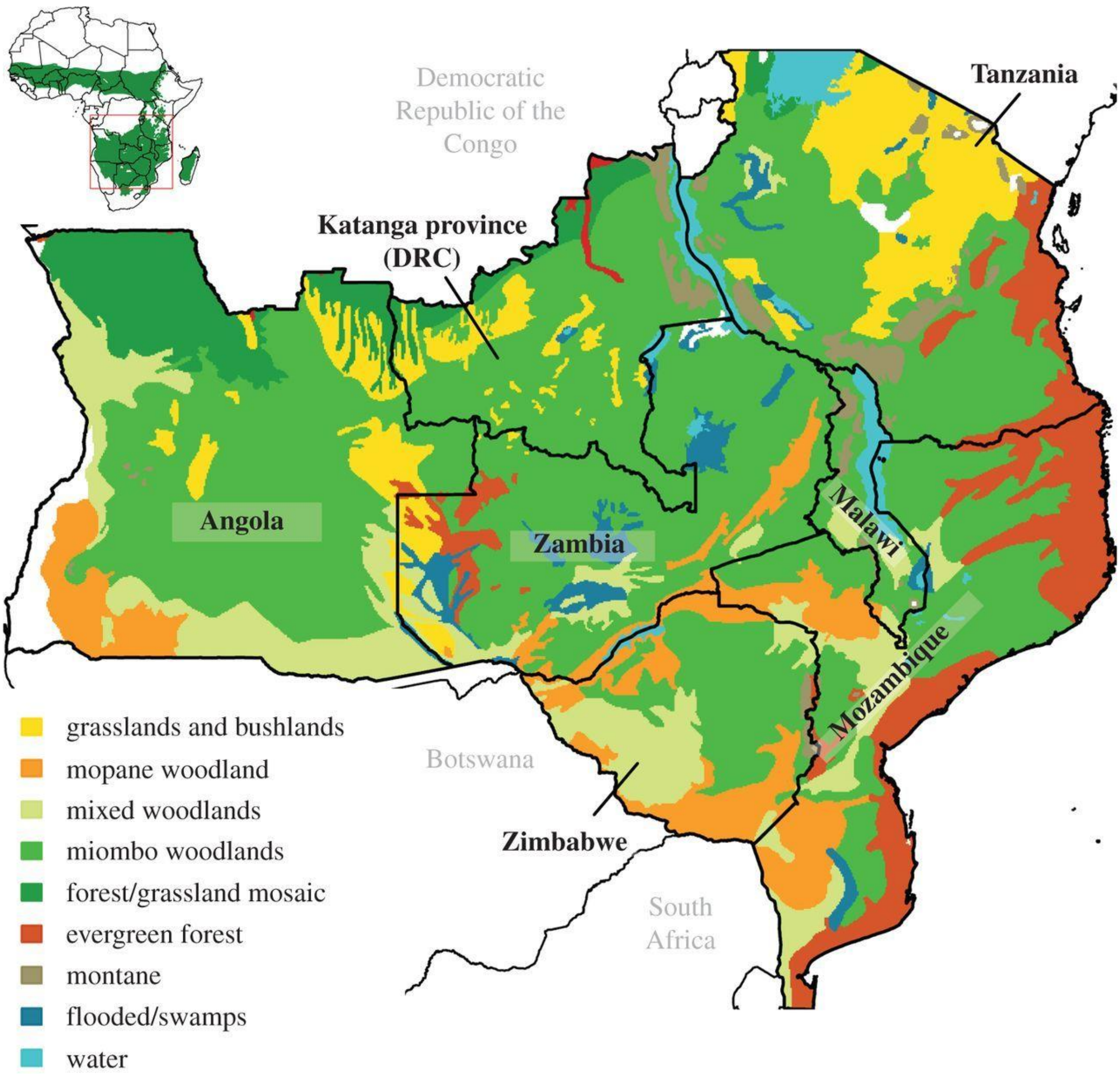

Figure 1.1 The potential extent of the miombo and mopane woodlands of southern Africa, obtained from Ryan et al. (2016). The map is based on vegetation maps and expert opinion, with land cover conversions (e.g. agriculture) not indicated. Inset shows the extent of African savannas.

Miombo woodland climate is characterised by alternating wet and dry seasons, though mean annual precipitation (MAP) is highly variable across the region. White (1983) distinguished between the species-rich wetter miombo (MAP >1000 mm) and species-poor drier miombo (MAP<1000 mm), with Chidumayo (1987) identifying several subtypes within wetter and drier miombo in Zambia. A recent floristic analysis based on the Socio-Ecological Observatory for Southern African Woodlands (SEOSAW, 2020) dataset identified three miombo subtypes – named for their most representative genera after *Brachystegia*, *Julbernardia* and *Isoberlinia* – as 1) *Hymenocardia/Uapaca* miombo, 2) *Diplorhynchus* miombo, 3) *Combretum* miombo (Ribeiro et al., 2020c). These subtypes are geographically intermingled in the miombo region rather than being continuous, along with several other non-miombo floristic groups.

The dominant miombo genera are endemic to tropical Africa and determine much woodland diversity and functioning (Moura et al., 2017), including nutrient and water cycling (Chidumayo, 1997), as well as human use. Typical miombo species such as *Brachystegia spiciformis*, *Brachystegia boehmii* and *Julbernardia globiflora* are used as construction materials, as woodfuel, in apiculture and in traditional medicine (Grundy, 1995; Moura et al., 2017). Valuable timber species such as *Pterocarpus angolensis* and *Dalbergia melanoxylon* are used both locally and for export (Ball, 2004; Moura et al., 2017). Generally, animal diversity is relatively low though there are a number of endemic bird species such as the Miombo Grey Tit and Miombo Rock Thrush, as well as charismatic large mammals (Frost, 1996). Some miombo fauna have disproportionate effects on their habitat: perhaps most starkly, elephants reduce woody cover (particularly of their preferred browse species) (Caughley, 1976; Mapaure & Moe, 2009) and *Macrotermes* termite mounds support distinct plant assemblages, acting as a refuge for many mammal and bird species (Fleming & Loveridge, 2003; Joseph et al., 2011).

Palaeoecological and experimental evidence suggests that climate and disturbances such as fire and herbivory have been important determinants of the composition, structure and geographic extent of miombo woodlands for at least several thousand years (Trapnell, 1959; Morris, 1970; Lawton, 1978; Vincens et al., 2003; Ekblom et al., 2014; Ivory & Russell, 2016). Many trees are adapted to disturbances such as fire, with the ability to resprout (Grundy, 1995; Ryan & Williams, 2011) and/or with adaptations to protect important tissues from fire. For example *Combretum*, *Terminalia* and *Pterocarpus* seeds are protected by indehiscent fruits (Chidumayo, 1997). Often in miombo trees, important phenological phases such as leaf flush happen outside the main fire season. In herbaceous species, above-ground tissues tend to die during the dry season, when the risk of fire is greatest, and buds are protected by being low to or below the ground.

Fire and herbivory have continued to shape miombo woodlands (Mapaure & Campbell, 2002; Ribeiro et al., 2008), while growing human populations and governance of miombo countries have had variable impacts on their woodlands during recent history and into the present day (Ribeiro et al., 2020a). For example, colonial era tsetse eradication policies included bush clearing and resettling human populations, resulting in the regeneration of some areas of woodland and the destruction of others (Misana et al., 1996). Shifting cultivation remains widespread in miombo countries; studies in Mozambique (Williams et al., 2008) and Tanzania (McNicol et al., 2015) found that different tree species were represented on re-growing abandoned fields versus old growth miombo. However, the studies also found that diversity was comparable between sites and that tree carbon stocks recovered in abandoned fields within a few decades.

The cumulative effect of human activities in the miombo in recent decades has been a reduction in woodland cover, driven primarily by agricultural expansion, charcoal production, climate change and population growth (Dziba et al., 2020). Current wooded area totals around 2.0 million km^2, with around 0.6 million km^2 of the miombo's former range having now been converted to cropland and 0.1 million km^2 being natural non-wooded land. This has raised concerns about the future of the miombo and the services they provide to people (Ryan et al., 2016; Dziba et al., 2020).

1.3 Degradation narratives and fire management in Africa

The term 'degradation', when used to describe processes related to the state of a landscape, implies a reduction in the usability of land (Blaikie & Brookfield, 1987). Perceptions of whether land is degrading or degraded may depend on ecological conditions, politics, economics, and the vested interests of different groups. For example, an area of woodland converted to an agricultural field may be considered degraded by a conservationist but enhanced by the farmer who is now able to eat and earn money from this land. Degradation therefore inherently relates to human valuation of nature, and decisions about how best to manage it.

Throughout most of human history in southern Africa, judgements about how to manage land were made at the local level, often by traditional rulers, to meet multiple individual and community aims. This management history cannot be separated from the history of fire, which has shaped African savannas for millions of years (Scott, 2000; Edwards et al., 2010; Veldman et al., 2015; Gowlett, 2016). Fire has been controlled by people to a significant degree for 400 000 years (Bird & Cali, 1998), with human impacts on fire regimes increasing in the past 4000 years, due mainly to changes in landscape connectivity and burning associated with agropastoralism (Archibald et al., 2012). Today, humans continue to impact fire regimes directly through ignitions (Archibald et al., 2010), setting fires for reasons such as creating fresh grazing, improving visibility, deterring dangerous animals, and for field preparation (Hough, 1993; Eriksen, 2007; Butz, 2009; Shaffer, 2010). Humans impact fire regimes indirectly by altering landscapes and the climate (Bowman et al., 2011).

During the 19th and 20th centuries, control over land management shifted to new colonial powers in many African countries. Colonial authorities typically valued forest over other vegetation types. They saw local land management activities as 'primitive' and a threat to natural assets, particularly economically valuable timber species (Pooley 2021). Ecological theory and burning experiments conducted by European scientists (e.g. Aubréville, 1947; Trapnell, 1959) sparked concerns that fires, particularly in the late dry season, halted the succession of vegetation to a desired 'climax' forest state. These views were compounded by beliefs that burning could contribute to soil erosion, a fear stoked by the American Dust Bowl experience (Pooley 2021). Fire suppression policies aiming to conserve trees, were subsequently implemented (Lovett, 2003; Kull & Laris, 2009). Prescribed burning early in the dry season (when fires burn less intensely and remove fuel available for more intense late dry season fires) was also applied in some cases, as early fires were considered a less destructive alternative to late fires, and more practical to implement than total fire suppression. Any research and management experience suggesting that fire use could offer environmental benefits was largely disregarded in the context of this strong anti-fire rhetoric (Pooley 2021).

Timber and other forest resources remained economically valuable for many newly independent African nations from the 1960s onwards, and some colonial approaches to natural resource management persisted. Growing international environmental and conservation movements also reinforced colonial narratives about degradation and its causes. Today, trees and forests continue to be valued highly, though now often for the biodiversity they foster and carbon they store rather than timber (Bellassen & Luyssaert 2014) and there is widespread concern about their loss, frequently described as degradation. Perhaps most influentially, the UN Framework Convention on Climate Change (UNFCCC) framework for Reducing Emissions from Deforestation and forest Degradation (REDD+), defines degradation as loss of trees from a patch of forest or woodland. There is evidence that this process is more prevalent than deforestation in miombo woodlands (McNicol et al., 2018a).

Concern about loss of trees via 'degradation' by the UNFCCC definition therefore underpins academic studies, international treaties and, as a result, national policy and local management in Africa. Several countries have REDD+ strategies aiming to limit this kind of degradation (see the REDD+ website for a list), with environmental organisations running local-scale REDD+ projects. Reinforced by, for example, the Convention on Biological Diversity (CBD; see section 1.7 for more discussion of this) and communications from environmental NGOs (e.g. WWF 2021) is the persistent narrative that many traditional land management activities in Africa, including fire, drive this kind of degradation. Such narratives are repeated by local people (Gross-Camp, 2017) sometimes even in direct attack of their own livelihood practices. For example, Tanzanian farmers themselves have been reported as saying that removing trees for agriculture turns the land to 'desert' (Brockington, 2006).

Fire is often cited as a specific cause of degradation or a threat to woodlands and forests (e.g. Nssoko, 2002; Miya et al., 2012; Awono et al., 2014; Dokken et al., 2014; Kweka, 2014). This is expressed in national policies (for example see the discussion of Tanzania's fire policies in section 1.7) and in, for example, carbon certification schemes which financially reward tree restoration or avoided loss (e.g. Plan Vivo Standard, Project Requirements

Version 5.0). There are now also calls for management to reduce direct fire emissions (Houghton 2013).

Challenges to narratives that identify fire as a cause of degradation come from researchers who argue that miombo and other savanna woodlands are disturbance-driven ecosystems (Ribeiro et al., 2020a) incorrectly identified as degraded forests (Veldman et al., 2015, 2019). The simple model of ecological succession to a stable climax state is no longer accepted, and in parts of southern Africa with intermediate rainfall it has been demonstrated that fire maintains stable savanna systems alongside forests (Staver et al. 2011). Criticisms of colonial-era fire experiments have also mounted (as discussed in section 1.4).

There are now widespread calls for ecosystem management that considers an active role of fire in savanna dynamics from ecologists (van Wilgen, 2009; Veldman et al., 2015) and land managers (Everson et al., 2004), for environmental, practical, and social reasons. These have been heeded to some extent by conservation organisations using prescribed burning to manipulate rather than suppress fire regimes. However, this fire management technique (which, as noted above, was also used by colonial foresters) is still employed based on the assumption that fire use by local populations, especially late in the dry season, is environmentally degrading. Prescribed burning is seen as necessary to reduce the impact of late fires on trees (e.g. Mpingo Conservation and Development Initiative et al., 2015).

Since colonial times in many parts of Africa, and in savanna regions the world over (Moura et al., 2019), dominant degradation narratives have therefore been simplistic: often defining degradation by a loss of tree cover alone. Today, at their most extremely reductive, trees are equated merely to ‘carbon sticks’ and the multiple other benefits from complex woodland and forest ecosystems are ignored (Jacob et al., 2014). This narrative has gone hand in hand with a continued characterisation of local land management activities, including fire (be it all fire or late season fire only) as a driver of degradation.

This is despite, as discussed in the subsequent section, the ever-growing body of evidence demonstrating that the ecological impacts of fire are far more complex than such narratives concede: benefiting some species while harming others. These narratives also ignore the multitude of ways that fires and fire-prone ecosystems can be valued by people. Understanding these alternative views on how to value and manage land is therefore key to challenging simplistic narratives voiced by powerful groups, and to developing successful fire management in social-ecological systems (Dawson & Martin, 2015).

1.4 Recent evidence and approaches to fire management

National parks have long been the focus of fire management research and practice in Africa (Nieman et al., 2021). In recent years, management and related research have often been guided by specific conservation goals, with fires being actively applied or suppressed to improve grazing for large herbivores, reverse woody encroachment, control unwanted species or protect desirable ones. Attempts to exclude anthropogenic fires – whereby fires started by lightning are allowed to burn but fires started by humans are suppressed – have also been implemented in Etosha National Park, Namibia, and Kruger National Park, South Africa. However, this has had limited success partly because of the inevitability of human-caused fires (Trollope & Trollope, 2004). In Kruger National Park, other approaches – for example using a combination of prescribed fires and unplanned fires encouraged to burn an annual target area – have been trialled over the years (van Wilgen et al., 2008).

Prescribed burning early in the dry season has been widely advocated by academics and land managers because it is associated with a number of benefits (Nieman et al., 2021). For example, fires across African savannas contribute significantly to global carbon emissions (estimated to represent 14% of emissions from fossil fuel burning; Ramo et al., 2021), and some have argued that emissions could be reduced if more burning was shifted to the early dry season via a reduction of the total area burned (Lipsett-Moore et al., 2018). The reduced intensity of early dry season fires could also enhance aboveground carbon storage in trees (Ryan & Williams, 2011; Gumbo et al., 2018).

Patch mosaic burning – whereby burning is conducted on small patches, and carried out at different times throughout the year to create a landscape mosaic of vegetation with different burn histories – is also used in many national parks with the aim of maintaining habitat heterogeneity, which is assumed to increase biodiversity (Kelly & Brotons, 2017).

Prescribed burning, particularly early in the dry season (sometimes as part of patch mosaic burning) is frequently suggested in academic literature as a way to avoid conflict with local communities who use fire for livelihood activities while achieving environmental goals such as these (e.g. Eriksen, 2007).

However, the evidence for the proposed benefits of early burning is mixed. Laris and colleagues (2016) argue that many fire experiments comparing the effects of early and late burning (e.g. back to the early and still highly influential studies of Aubréville, 1947) represent extremes of burning seasonality and that, in West Africa at least, most fires occur in the middle of the dry season. The authors argue therefore, that much experimental evidence cannot be straightforwardly applied to understanding the fire-regimes of lived-in landscapes. Furley et al. (2008) point to further flaws in the design of fire experiments including small plot sizes and rigid burning schedules which do not represent typical conditions of fire-prone ecosystems.

Laris (2021) criticises Lipsett-Moore et al. (2018)'s fire emissions model noting that, while shifting burning to the early dry season in Africa may reduce the total area burned, any subsequent emissions reductions may be offset by increased methane emissions generated due to the higher moisture content of fuel at this time of year. Research also shows that patch mosaic burning may benefit some species but not others (van Wilgen et al., 2004, 2008; Parr & Andersen, 2006). Finally, it may not always be the case that early dry season fires meet the fire needs of communities (Hough, 1993).

In light of the mixed picture of the costs and benefits of different fire regimes, in recent years there have been calls internationally for integrated fire management (IFM) (Mistry et al., 2018; McWethy et al., 2019). Meyers (2006; p. 2) defines IFM as: "The integration of science and society with fire management technologies at multiple levels. It implies a holistic or seamlessly-woven comprehensive approach to address fire issues that considers biological, environmental, cultural, social, economic and political interactions". While the definition varies between users, at its core IFM aims for a more holistic understanding of the role of fire and approach to its management (Moore, 2019; Castro Rego et al., 2021). Whereas historical fire management has typically been guided by narrow goals such as timber preservation (see section 1.3), IFM seeks to maximise the net benefits of fires by considering the ecological and social context. Versions of IFM have been applied in Australia, South America, Europe and Africa to varying degrees (Castro Rego et al., 2021).

The application of IFM has been limited in Africa but there are some examples of community-based fire management inspired by IFM. For example, fire management heavily based in traditional practices in a community forest in The Gambia was cited as a success by researchers – partly due to the use of traditional methods and because participants felt a high degree of ownership over the community forest they were protecting from fire (Sonko et al., 2002). However, the same authors reported that involving local villages in fire management for the national park was far more fraught. Approaches such as employing labourers from some of the park's surrounding villages generated envy from those not involved in fire management. Additionally, people felt that because they had lost rights to the resources available from the national park, any involvement in its protection (including fire management) should be paid for.

Internationally, the track record for truly integrating local knowledge and values into formal fire management strategies appears to be fairly poor. Indeed, many IFM 'success stories' described by academics and land managers in a recent book chapter (entitled Integrated Fire Management; Castro Rego et al., 2021) do not involve local communities at all. Where communities have been involved in fire management, often local people are trained in fire management theory and methods by 'experts', rather than their knowledge contributing to the technical understanding of fire behaviours and impacts and development of management strategies (Eloy, 2019; Pooley, 2021).

As fire continues to be necessary for various livelihood activities, most fire management in Africa remains in the hands of its rural populations. This kind fire use is still widely discouraged in national policies and legislation, which continue to reflect narratives that fire causes degradation (Laris, 2002; Kull, 2002; Eriksen, 2007; Shaffer, 2010; also see previous section). Yet – with most fire research having been conducted in national parks – few studies have explored the causes and impacts of fire in these inhabited landscapes. This undermines truly integrated and sustainable fire management in places where humans live and use fire.

1.5 Research aims and objectives

In this thesis, I aim to address some of the assumptions and evidence gaps resulting in a biased academic understanding of African fire regimes, which subsequently inhibits successful fire management.

As outlined in section 1.3, fire (particularly late dry season fire) is widely cited by conservationists as a cause of environmental degradation in Africa. In particular, fires are assumed to cause tree loss (with this being the definition of 'degradation' by the UNFCCC, governments, and environmental organisations). However, the evidence for this is based mainly on biophysical experiments in protected areas, which do not represent most fire regimes (section 1.4). In chapter 3 of this thesis, I address this assumption by identifying the impacts of the fire regime on trees in a lived-in miombo woodland in Tanzania, using a long-term dataset. I focus on large trees, which are rarely studied, despite being important providers of ecosystem services, including biodiversity and carbon storage.

As discussed in sections 1.3 and 1.4, while degradation narratives elevate conservationist perspectives, local perspectives of fire are rarely studied. Therefore, in the chapters 4 and 5 I shift focus to local people, who set fires and live with their proximate impacts each year. In chapter 4, I explore the role fire plays in livelihoods, and the extent to which the fire regime is intentional. I aim to identify whether the current fire regime is shaping the land in a way that is considered useful, degrading, or both. In chapter 5 I aim to understand the social impacts of fire in greater depth, by analysing the consequences of fire, good and bad, for local people's wellbeing. These chapters therefore contribute to a richer understanding of whether and how fire may cause degradation, and how different aspects of the fire regime can be considered beneficial or harmful from different perspectives.

My overarching research objectives are:

1. To assess the extent to which fire is driving degradation (from a conservationist perspective) in miombo woodlands, by establishing tree demographic rates and exploring how large trees are impacted by fires.
2. To understand why people set fires in miombo woodlands, and how intentions impact the resulting fire regime.
3. To assess the perceived role of different types of fire in achieving local wellbeing goals.

1.6 Introduction to the study site: Kilwa, Tanzania

The case study site for this thesis is Kilwa District, in the Lindi Region of south-eastern Tanzania (a detailed description and study site map are given in section 2.2). Kilwa represents a useful case due to its dominant land cover of miombo woodlands though it also includes patches of East African coastal forest (Burgess & Clarke, 2000). Permanent sample plots were established across Kilwa District between 2010 and 2011 (McNicol et al., 2018b), enabling long-term monitoring of woodland dynamics (SEOSAW, 2020) including the tree loss and regrowth dynamics indicated by remote sensing (McNicol et al., 2018a).

Kilwa is also home to a number of fire-based livelihood activities common to other African savannas, including agriculture, pastoralism and charcoal production (Miya et al., 2012), which historically have been significant drivers of change in miombo ecosystems (Dziba et al., 2020) and are commonly cited causes of deforestation and degradation in Tanzania and elsewhere (Miya et al., 2012; Kessy et al., 2016; Doggart et al., 2020). In Kilwa, communities burn around their community woodlands to protect carbon and timber stocks (Mpingo Conservation and Development Initiative et al., 2015). Aside from this, there are some environmental regulations, including those about fire from the national government, though these are found embedded within other policies related to land management (e.g. the Forest Act; Parliament of the United Republic of Tanzania, 2002) rather than a dedicated fire policy (FAO-Finland Forestry Programme – Tanzania, 2013). A brief history of relevant policies in Tanzania are given in the following subsection.

1.7 History of land and fire management in Tanzania

Prior to colonisation, Tanzania was primarily a subsistence economy in which natural resources were managed according to local culture and customs, including traditionally protected forests and trees (Ylhäisi, 2003). The colonial period (1891 until 1961, under German followed by British administrations) involved widespread designation of forest reserves with the aim of protecting resources, particularly economically valuable timber (Burgess & Clarke, 2000). Many reserves were established during the early decades of colonisation, but the British administration (from 1918) gazetted large additional areas of miombo woodland after improvements to the railway network enabled easier exploitation of these areas (Ylhäisi, 2003). Large forested areas were also cleared by German and British administrations for plantations of products for export, such as coffee (Coulson, 2013).

As in other parts of Africa, throughout the colonial period fire suppression policies and the displacement of local communities from traditional lands were common, in service of protection of forest resources which were seen as a public good threatened by the livelihood activities of local people (Burgess & Clarke, 2000). The restriction of peoples' land and resource access rights generated conflict and undermined the natural resource management which had traditionally been mediated via informal social conventions and the authority of traditional rulers (Ylhäisi, 2003).

Many environmental laws remained unchanged following independence in 1961 (Lovett, 2003). However, the villagisation policy orchestrated by the first President of Tanzania Julius Nyerere from the late 1960s resulted in the restructuring of rural communities, with subsequent impacts on land use patterns. Underpinned by the socialist ideology *ujamaa* (roughly translated as 'extended family'), the aim of villagisation was to concentrate scattered rural populations and semi-permanent settlements into communities, to enable social development and modernisation, for example via intensified agricultural practices and the provision of social infrastructure such as schools and hospitals.

Kikula (1997), studying five villages in Mufindi District of southern Tanzania found that villagisation resulted in undermining of traditional land management and intensified land use. While rural people retained and continued to apply traditional knowledge to land management, the author argues that the social, economic and physical changes associated with villagisation, over which local people had little influence, made land degradation inevitable. The rate at which populations concentrated in rural areas during this time outstripped the rate at which innovations in land-management could be developed (Kikula 1997).

Ylhäisi (2003) argues that in recent times officials have continued, as their colonial predecessors did, to perceive that local people harm their environment. Officials have attributed this to traditional conservation practices no longer being applicable to areas people are living in (as people have moved from traditional territories, and often encroach on protected land), population pressure, poverty, insecure land tenure, insufficient environmental legislation, and poor enforcement of environmental policy. However, simplistic narratives that local land management practices drive degradation certainly also have roots in discredited Western colonial-era ecological theory and flawed fire experiments (sections 1.3 and 1.4). These narratives are central to Tanzanian land governance at local and national levels (Brockington, 2006).

Since the 1990s, Tanzania's participation in international conservation initiatives such as the CBD and REDD+ have been highly influential of national environmental policies. These policies have widely framed fire as harmful and a threat to forests, e.g. see The National Forest Policy (Ministry of Natural Resources and Tourism, 1998) and the National Forest Programme in Tanzania 2001-2010 (Ministry of Natural Resources and Tourism Forestry and Beekeeping Division, 2001).

Tanzania's 2002 Forest Act (Parliament of the United Republic of Tanzania, 2002) recognises the need for people to use fire, allowing people to burn on their own land and elsewhere with permission from a government authority or the relevant land owner. It requires people to fully extinguish fires before they spread to land they do not have permission to burn. People can be fined if an uncontrolled fire they set burns someone else's property. Therefore, fire is allowed in Tanzania, but the ideal (indeed the legal requirement) is that it is highly controlled and contained within restricted areas. Reportedly in northern Tanzania, fire suppression has been encouraged to present lands in a state thought to be appealing for tourists (Butz, 2009), though maintaining open habitats through fire use can also be seen as important for tourist game viewing (Nieman et al., 2021).

Most of the protected areas established by colonial administrations are still recognised by the Tanzanian government. An additional 62 111 km^2 land area has also been designated for protection, with a total of ~40% (44 million hectares) of Tanzania's land area, mainly consisting of miombo woodland, protected with nature conservation aims (Ylhäisi, 2003). Around one quarter of this land area consists of occupied conservation or game controlled areas. Additionally, many more communities live adjacent to protected areas and depend on resources from inside or near to the reserves. A recognition of the need to include these communities in environmental management has resulted in the rise of participatory management in recent years.

For example, community-based forest management involves communities establishing and managing forest reserves on village land, while joint forest management involves communities collaborating with local government to manage an area of forest (Parliament of the United Republic of Tanzania, 2002). Participatory management has also included some community fire management which, generally, reflects national narratives that fire is harmful to the environment while recognising the benefits of fire use to local people (FAO-Finland Forestry Programme – Tanzania, 2012).

For example, the Tanzanian Government strategy for the conservation of Eastern Arc Mountain Forests (which are montane forests interspersed with miombo woodland patches; Shirima et al., 2011) identifies fire as a threat, and aims to increase community awareness and participation in fire management here (Ministry of Natural Resources and Tourism Forestry and Beekeeping Division, 2005). An IFM 'FireWise' approach – which was adapted from an approach developed in the USA and is underpinned by consideration of both beneficial and harmful effects of fire – has been trialled here (Tanzanian Forest Service, 2013). The approach involves a variety of community workshops and training sessions, including the development of a fire management plan.

While there were short term initial reductions in fire incidence following its application, so far the approach has not been successful in reducing fire incidence in the long-term. Kagosi et al. (2020) report that reasons for this include poor involvement of local communities and a discordance between the approach and the reality of fire use by local communities; this is reminiscent of findings elsewhere (see discussion of IFM in section 1.4). The authors write that the approach must be better adapted to suit the Tanzanian context. Findings elsewhere have also suggested that incorporating local traditions and a sense of ownership over fire management are key to successful community-based fire management whereby people are actively and willingly involved in controlling fire incidence and spread (Nssoko, 2004). However, this has rarely been achieved in practice (Kilawe et al., 2021).

1.8 Thesis outline

This thesis aims to present a case study exploring fire causes and consequences in the Kilwa District of south-eastern Tanzania at multiple scales and from multiple disciplines, based around three empirical research chapters. The empirical chapters have been written as academic articles, edited to reduce repetition (though there remains some overlap where unavoidable). Where these chapters have multiple authors, 'we' rather than 'I' is used to discuss the approach to the research. An outline of the thesis is given in this section.

Following on from the current introductory chapter which outlined my research objectives and justified the choice of study site, chapter 2 provides an overview of the methodology adopted during the empirical research. It introduces relevant theories and concepts, data collection methods, ethical considerations, and further details on the study site: Kilwa, Tanzania.

Chapter 3 uses data from miombo woodland plots in Kilwa to present an overview of woodland trends over nine years. The role of fire in the growth and mortality of large diameter trees, which are keystone structures containing one third of miombo aboveground carbon, is also assessed. I asked the questions:

1. How has the floristic diversity of large stems changed over 9 years?

2. How has aboveground carbon storage changed over this time?
3. What are the mortality, recruitment and growth rates of large stems?
4. How does fire influence stem growth and mortality?

In chapter 4, my co-authors and I present findings from interviews in rural communities to understand the role fire plays in local livelihoods. We then combine these data with remote sensing to explore linkages between fire intentions and the resulting fire regime. We asked the questions:

1. What are the main causes of fire (human or otherwise) in Kilwa?
2. What are the human intentions and livelihoods associated with fire use?
3. How do the intentions behind fire use influence fire regimes?

Chapter 5 presents data on interviews and focus group discussions and uses the capability approach to study, for the first time, the impacts of fire on multiple dimensions of wellbeing. I identify fire impacts in rural communities and relate them to broader wellbeing goals, asking the questions:

1. Which capabilities contribute to wellbeing in Kilwa farming communities?
2. How does fire act as a conversion factor i.e. a means to enable or inhibit achieving wellbeing goals?

In chapter 6, I synthesise the main findings from the empirical chapters in relation to my overall research aims and objectives (section 1.5) assessing what the research reveals about the causes and consequences of fire, their synergies and trade-offs in Tanzanian miombo woodlands. I discuss the implications of the findings for debates about degradation and IFM in southern African woodlands. Finally, I summarise the main conclusions and implications of the thesis.

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Chapter 2. Methodology

Field team measuring a woodland plot in Kilwa District, Tanzania (Ellie Wood, 2019).

Chapter 2. Methodology

2.1 The development of this thesis

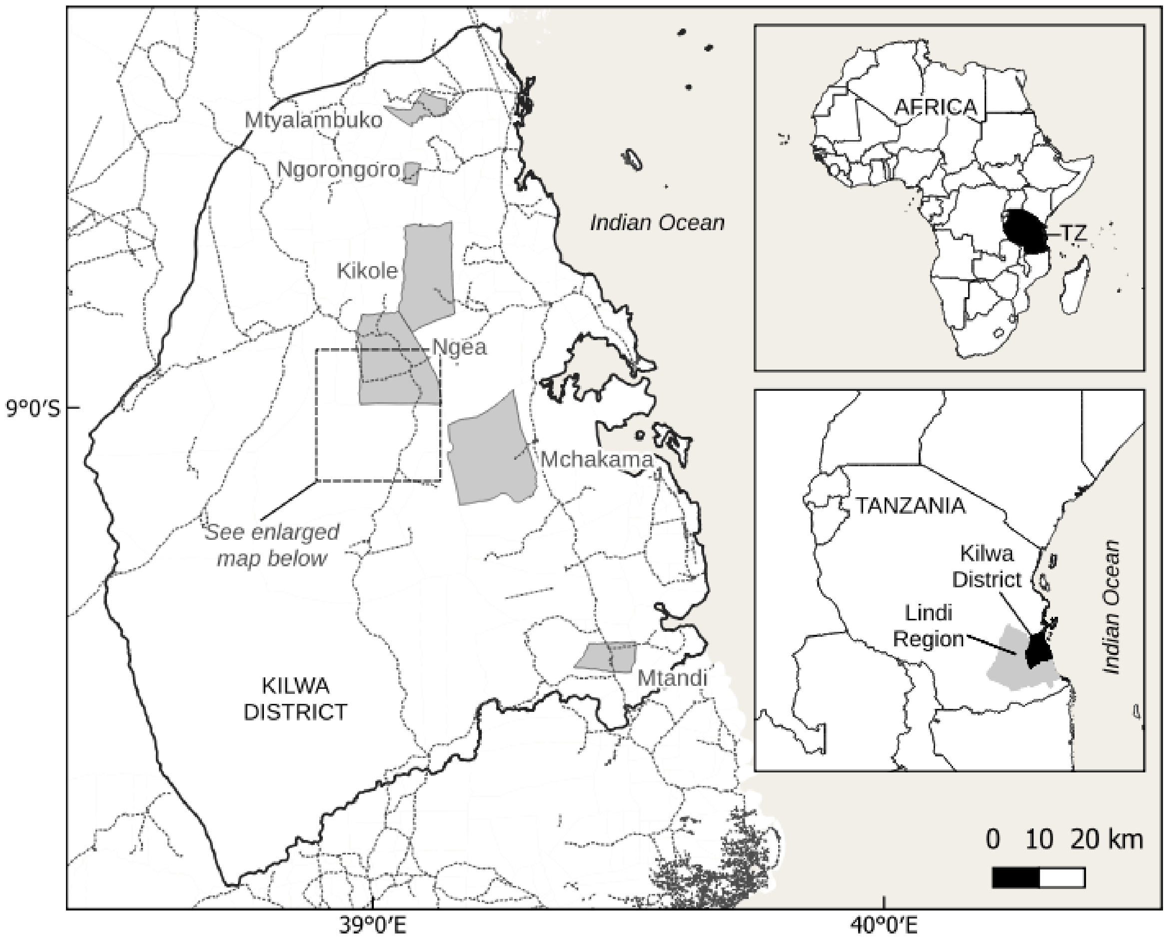
Due to the interrelationships between local people and miombo woodlands, and the ways in which they contribute to international concerns over biodiversity loss and carbon sequestration, management of the miombo must be informed by multiple disciplines and at multiple scales. Academic understanding of degradation in miombo woodlands must therefore be both social and environmental, both local and global: necessarily depending on a multitude of studies. In this thesis, I aimed to fill gaps in understanding of miombo woodland degradation, using natural and social science methodologies. My approach to the research, especially the development of research questions, was iterative and informed by literature from a wide range of academic disciplines, my interests and direction given by my supervisors, experiences during fieldwork and emerging findings. Practical considerations, opportunism and luck of course also played a role.

In all of the chapters, I led on: study design, data collection, analysis and writing of the manuscript. Two of the chapters contain major original contributions from others. Chapter 3 outlines findings from long-term woodland plots in Kilwa and therefore large portions of the dataset were collected by others: in particular, Iain McNicol, Casey Ryan, Mathew Williams, and many of the staff at Mpingo Conservation and Development Initiative. My design of the resurvey effort for this chapter was necessarily heavily based on the original study design by these researchers and on the SEOSAW (2020) protocol. In chapter 4, I led the overall research approach but limitations in my own skillset meant that I sought the help of Christopher Andrews who led the remote sensing analysis. Chapter 4 has multiple authors, so 'we' rather than 'I' is used to discuss the approach to the research; the specific contributions of each author are also detailed in this chapter.

The specifics of the methods used for data collection and analysis are given in the empirical chapters. In the remainder of this section, I explain the overarching approaches to the research, how and why this thesis developed as it did, beginning with an introduction to Kilwa.

2.2 Study site description

The case study site for this thesis is Kilwa District, in the Lindi Region of south-eastern Tanzania (section 1.6; Figure 2.1). The dominant land cover is miombo woodlands though there are patches of East African coastal forest (Burgess & Clarke, 2000). Precipitation is highest along the coast and lowest inland, with an estimated mean annual precipitation of 821 ± 350 mm (±SD). Altitude ranges from sea level on the eastern coast to 740 m.a.s.l further inland (McNicol et al., 2018). Typically, the rainy season is from November until May, with intra-seasonal droughts usually lasting several weeks between January and March. The dry season is from June until October. The population is approximately 85% rural and primarily dependent on natural resources for their livelihoods, and several livelihood activities involve the use of fire (Miya et al., 2012).


Mtyalambuko
Ngorongoro
Kikole
Ngea
Mchakama
Mtandi
Indian Ocean
See enlarged map below
KILWA DISTRICT
9°0′S
39°0′E
40°0′E
0 10 20 km
AFRICA
TZ
TANZANIA
Kilwa District
Lindi Region
Indian Ocean

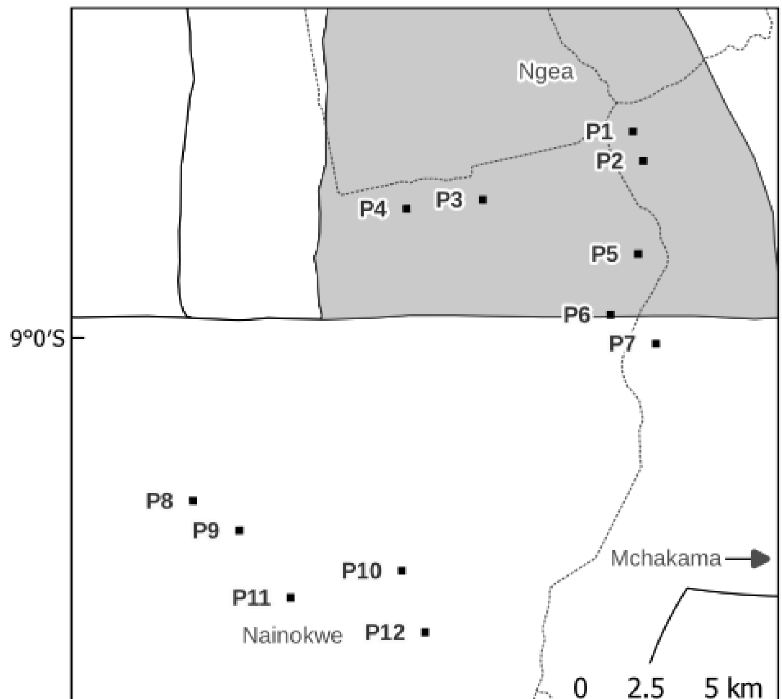

Ngea
P1
P2
P3
P4
P5
P6
P7
P8
P9
P10
P11
P12
Nainokwe
Mchakama
9°0′S
39°0′E
0 2.5 5 km

Figure 2.1 (above) Study site in Kilwa District, Tanzania. Top: the six study villages, indicated in grey in the main map, as located in Kilwa District within the Lindi Region of Tanzania ('Tz' in the top inset map). Below: an enlarged section of the main map showing the 12x 9-hectare woodland plots (P1 to P12; the black squares indicating the plots are to scale), with solid lines indicating village boundaries. Dotted lines indicate major roads.

Interviews and focus group discussions were held in six study villages in Kilwa – Kikole, Mchakama, Mtandi, Mtyalambuko, Ngea and Ngorongoro (chapters 3, 4 and 5) – with Ngea and another village, Nainokwe, also acting as a bases for ecological fieldwork (chapter 3; Figure 2.1). Study villages were chosen to represent a variety of population sizes, and to be geographically dispersed. I aimed to include villages at various distances from major roads as access to major population centres can impact livelihood strategies (Ahrends et al., 2010). For example, villages on the main roads connecting with Dar es Salaam to the north of Kilwa District (especially the north-south road which runs through Mtandi and adjacent to Mchakama; Figure 2.1) may produce more charcoal (Malimbwi & Zahabu, 2008).

Historically in Tanzania, different geographic areas were occupied by particular tribal groups, whose livelihood activities were suited to the region; for example, fishing by traditionally coastal tribes. During Tanzania's colonial period many communities were displaced. This continued under villagisation policy during the early years of independence, whereby dispersed rural populations were concentrated into village communities (section 1.7). Subsequently, each study village now represents several tribes with different histories, traditions, and languages.

The most common tribes in the study villages include Makonde, Matumbi, Mwera, Ngindo, Nyasa, and Yao. Generally tribal affiliation no longer defines a person's day-to-day life, livelihood strategies or interactions with others in the village. Most households are arable farmers growing a mixture of subsistence and cash crops. Some people are involved in livelihood activities that are (almost always) additional to farming, including hunting, charcoal production, honey collection and logging. All villagers primarily speak the national language of Swahili, though some words in local and tribal languages are used. Most residents do not remember the country before independence and villagisation from the late 1960s and, for many, their ancestors have lived in the village (or at least in the area) for multiple generations. Interview respondents often said that they *live like one family* in their village.

Since the changes brought on during the colonial period and independence, there are also no longer traditional (tribal) authorities overseeing natural resource management. In each village, the local authority is the Village Office headed by the Village Executive Officer (a government employee who typically comes from outside of the village) and there are several elected committees, including the Village Committee headed by the Village Chairman, and Village Natural Resources Committee.

Attitudes towards natural resource management are influenced by conservation narratives filtering down from central and local government and environmental NGOs in Tanzania (Brockington, 2006; Gross-Camp, 2017). In general, and in-line with these Eurocentric narratives common in many African countries (section 1.3), fire is seen as harmful to the environment despite being necessary to many livelihood activities. Religion also shapes attitudes towards the environment. The majority of people in the study villages are Muslim, with some Christians, and many reported that it is bad to harm "God's creation", including the perceived destruction caused by fire (for example, if animal habitats are burned). Traditional knowledge continues to inform natural resource management including fire use, for example when burning for agriculture or to create fire breaks. Many respondents reported that these methods were taught by their parents and grandparents and have been used for generations.

Small populations of pastoralists from the Sukuma tribe live in or close to all the study villages, having moved from their traditional northern range and arriving fewer than 10 years ago in most cases. The Sukuma peoples' main livelihood is keeping livestock to sell meat and milk, but most families also grow crops. There is tension between some of the Sukuma people and other members of the village, with Sukuma people tending to live far from village centres and being less integrated in village affairs. Unlike the main village community, these groups are relatively insular and consist of only members of the Sukuma tribe. One Sukuma woman I spoke to did not speak Swahili, only her tribal language (her daughter translated between Sukuma and Swahili during our interview, while Mercy Mgaya translated between Swahili and English). We were only able to interview five Sukuma people in total, limiting my understanding of this tribe in Kilwa, but my impression was that their perspectives on land management were less influenced by external environmental narratives than those more integrated in permanent villages. Their perspectives and activities seemed to be driven more by experience and traditional knowledge.

Some farmers in the main village fear Sukuma people, as stories are told of those who have been beaten and killed by members of this tribe. Others argue that Sukuma livestock keeping degrades the land. Farmers complain Sukuma-owned livestock eat their crops, while Sukuma people complain that farmers lie about this to receive compensation from them. Sukuma tend to be wealthier than other village members, and some feel that there are unwarranted negative feelings and jealousy towards their tribe. However, some farmers and Sukuma state that relationships are good, or simply non-existent between their communities. Several Sukuma people who moved to Ngea contributed money to a community project, and others in this village have cited this as an example of how the Sukuma people and other villagers live well together.

There is a mixture of formalised land management approaches in Kilwa District, with community-based forest management in several of its villages (Khatun et al., 2017) established by the local non-governmental organisation (NGO) Mpingo Conservation and Development Initiative (MCDI). The primary goal of this management is to sustainably harvest and sell timber species, generating funds for the communities. To this aim, there are restrictions on harvesting in the community forests, and prescribed burning is conducted around their borders to protect them from later uncontrolled fire.

The timing of prescribed burning varies from year to year and village to village. The aim is to burn when the grasses are dry enough to carry a fire, but still have a relatively high moisture content (in the early dry season, typically May or June) so that the resulting fires are easier to control. Logistical and financial factors also affect the timing of prescribed burning and it is not always carried out at the optimal time – rather, burning sometimes occurs later in the dry season when the grasses are much drier. Typically, the beginning of July marks the onset of the late dry season, when grasses have fully cured and more intense fires burn. However, respondents reported that this varies from year to year: burning activities, like farming activities, are dependent on the weather rather than a calendar date.

I studied both villages where MCDI worked, and where they did not. This is because I wanted to establish whether MCDI's activities in general, and prescribed burning in particular, influenced perspectives towards fire use (relevant findings are discussed in chapter 4). MCDI operate in three of the study villages (Kikole, Mchakama and Ngea), with designated community forests established in each of these. I found that those involved in community forest management in these villages generally see it as being effective. Gross-Camp (2017) also reports widespread positive attitudes towards community forest management in Kilwa, though the author presents findings that it does not provide real benefits for wellbeing. There is evidence that deforestation and degradation rates, at least in the short term, are reduced inside compared to outside the community forests (Brade, 2021). Aside from prescribed burning around the borders of community forests, there is no burning organised at the community level in Kilwa.

I conducted ecological fieldwork at 12 of the woodland plots previously established across Kilwa District (McNicol et al., 2018) (Figure 2.1; section 2.3.4). These plots were established by researchers in collaboration with MCDI. All plots were in village administrative boundaries of either Ngea or a village to the south called Nainokwe (Figure 2.1), and these villages acted as bases for the fieldwork. Ten of the 12 plots were in government reserves, while one (P11) was in communal village land and another (P12) in Nainokwe village community forest.

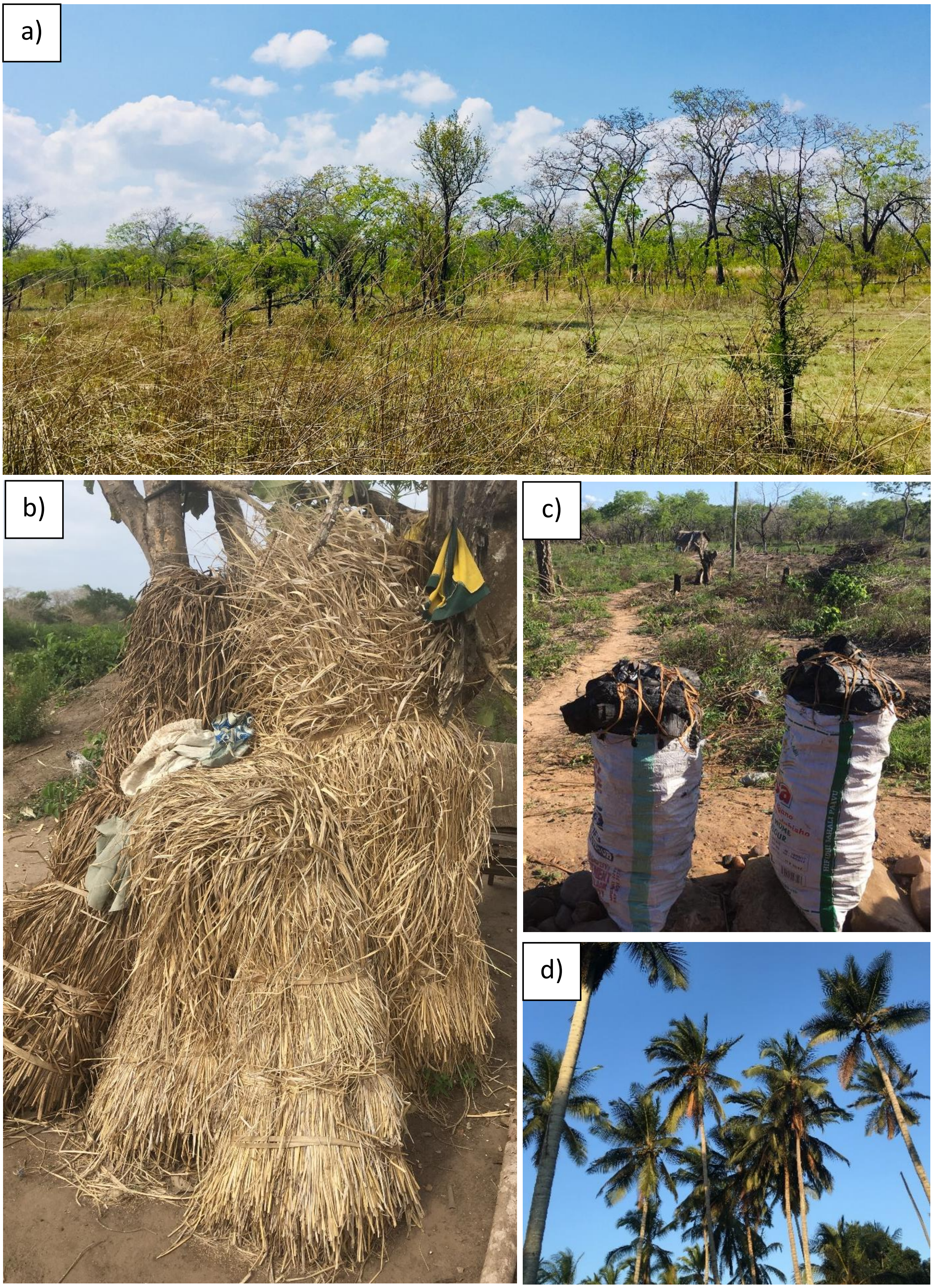
Legally, government reserves are managed by the Tanzanian Forest Service for sustainable timber harvest or nature conservation (Parliament of the United Republic of Tanzania, 2002). Their management has caused some conflict in communities in Kilwa – with respondents in Mchakama even reporting that people have been evicted from their homes on government land. Respondents also reported that government reserves were generally poorly managed, stating for example that resource extraction and fires were damaging the reserves, and that the government weren't doing enough about it.

Nainokwe's community forest is managed, with the support of MCDI, for sustainable timber harvest. There are restrictions on resource extraction, and prescribed burning is conducted around the woodland border. I did not collect enough data to fully explore how well these interventions are implemented in this village, though there was evidence of both timber extraction (which may or may not have been included in sustainable management plans) and recent fire on the plot when we surveyed it in 2019.

In communal village land, resource collection for household use is allowed. People are also legally allowed to burn on their own land and elsewhere with permission from a government authority or the relevant land owner (Parliament of the United Republic of Tanzania, 2002) (see further details of the Forest Act in section 1.7).

In practice, some amount of resource extraction and burning occurred on all of the plots between survey periods without legal regulation. I know this from discussions with local people and a government employee who assisted with woodland inventory on government land, and due to other indicators such as marks left by an axe rather than an electric chainsaw on tree stumps, and burned vegetation. However, all plots were several kilometres away from the main village settlement areas and at least 1 km from any roads and tracks, limiting human access to these areas – particularly for resource extraction, which people choose to do close to their homes when possible. As will be discussed in chapters 4 and 5, burning outside of an individual's own land is rarely legally regulated, and uncontrollable fires can spread great distances, often bypassing firebreaks and other attempts at control.

Photos of the study site are given in Figure 2.2.


a)
b)
c)
d)


e)


f)

Figure 2.2 Images of the study site in Kilwa District, Tanzania, showing a) miombo woodland near Ngea (2017); b) bundles of thatching grasses in Kikole (2018); c) charcoal for sale on the roadside (2017); d) coconut trees in Ngorongoro (2018); e) livestock kept by members of the Sukuma tribe in Mtandi (2018); f) walking interview with Mercy Mgaya and research participants, passing through agricultural area with banana plants, in Mbwemkuru (2018); g) woodland patch around Kikole cleared and burned to clear land for agriculture (2018). All photos taken by the author.

2.3 Research approach

2.3.1 Ontological and epistemological positions

My academic background prior to starting my PhD was in biology and ecology, and therefore based on a positivist epistemology assuming a single reality which can be studied objectively. In the latter stages of my undergraduate degree I became interested in environmental management and, more broadly, human-nature interactions. Prior to starting my PhD, volunteering in South Africa and Madagascar exposed me to environmental research and conservation projects with vastly different approaches to the inclusion of local people. The problems with the more exclusionary projects, as I saw them, and the benefits of the inclusive projects, further prompted me to pursue research which included local perspectives, and therefore, social science. I spent much of the early stages of my PhD reading social science textbooks and articles to familiarise myself with what were to me new theories, concepts and methods. Amongst much other influential work, the conclusion from Evely et al. (2008) challenged my assumptions about how research could and should be conducted:

> "The philosophical positions within research are not simple static positions and researchers should not rely on research traditions to select a research strategy, instead of selecting the most appropriate method. A fixed philosophical view of conservation when working with social sciences can do little to help sustainability. If a positivist approach dominates social–ecological research, research will mostly be limited to a quantitative approach, reducing methodological possibilities and limiting understanding of social phenomena driving conservation problems."

My status as a novice social scientist and my enthusiasm for what I was learning meant that my pilot fieldwork and early stages of research design were heavily guided by my reading at this stage, as was my ontological and epistemological approach.

I adopt a realist (also termed 'critical realist') perspective for this research. I assume there is an independent physical reality linking the social and ecological aspects of degradation in miombo woodlands, but that my research cannot independently appraise this relationship because I am a subjective observer (Sumner & Tribe, 2008). My research findings are partial because the reality is inherently complex and dynamic, and because my perspective as a researcher is influenced by my own context. With this in mind, attempting to understand the multiple realities of others – particularly those living in the woodlands I have studied – is a core underpinning of my research approach. This, of course, is central to much environmental social science work, but following my experiences as an undergraduate and conservation volunteer, this focus was new for me and very important.

Bevan (2006) poses two key questions for realists to ask themselves of their research: "is it practically adequate at this point in time?" and "what research might be done that would increase adequacy"' I held these questions in mind at key moments during research design, data collection and analysis – in particular, as I discuss next, in aiming not for the generalisability aspired to by positivist scientific traditions but for useful and adequate research.

2.3.2 Developing a mixed-methods case study: key research decisions

Given the time and financial constraints of a PhD, decisions have to be made about how to balance the trade-off between breadth versus depth of knowledge, considering the scale at which research is conducted and the methods used. On opposite ends of a spectrum are the in-depth single case study, versus the shallower study of multiple comparative sites. I describe this thesis as a mixed methods case study: one in which I aimed for a depth of understanding in some aspects of the research (chapters 4 and 5) and breadth in others (chapter 3) focusing on the Kilwa district of south-eastern Tanzania, and using methods from multiple disciplines.

I first visited Kilwa on a scoping study during November 2017, just two months into my PhD. The trip was suggested by my supervisor Casey Ryan, who had worked in Kilwa with MCDI previously, as an introduction to the miombo and some of the rural communities living there. Casey told me about MCDI's prescribed burning – a novel intervention in Africa. I decided to go to Kilwa for two weeks, aiming to gain at least some experience in which I could ground further decisions I made during the first year of my PhD. Coming from a natural sciences background, it was a chance for me to conduct interviews for the first time, to see MCDI's work (including visiting some of the woodland plots I would later resurvey), and decide whether Kilwa would be a good study site. I worked with MCDI throughout the scoping trip and hired one of their employees, Iddi Hamisi, to help organise interviews and act as a translator in the villages (where the vast majority of people speak Swahili). I asked respondents questions about fire, being particularly interested in the social and ecological impacts of MCDI's prescribed burning around community forests.

It was after this scoping visit that I decided to restrict my study to Kilwa District. For reasons outlined in section 1.6, Kilwa is a useful place to study miombo woodlands and rural communities living there. The presence of MCDI in Kilwa also provided practical benefits. The NGO has a history of working with researchers, and could provide advice, staff, and administrative support throughout the work. The possibility of working directly with MCDI, or for my research to support their work in some way, also appealed to my aim of conducting practically useful research.

I learned from this initial trip that I was interested in the prescribed burning as well as the livelihoods represented in the study villages – many of them fire-based – and the opportunity to resurvey the woodland plots for a longitudinal study. I learned that fire use was a sensitive topic and that I would need to spend time building trust in the study communities. I wanted to study a wide range of fire uses and impacts, which vary at the individual level. Therefore, I aimed to keep the scope of the study relatively restricted, to identify different perspectives within communities rather than conducting multiple community-level studies which falsely assumes homogeneity between individuals (Agrawal & Gibson, 1999). As a novice social scientist who had never lived in Tanzania but who wanted to understand complex and context-dependent realities, I felt that longer periods spent conducting detailed case study research at a limited number of sites would be best suited to this (Flyvbjerg, 2006).

For the social aspects of my research, I chose to study six villages in order to make comparisons between and limited generalisations within them (Yin, 2013). I studied both villages where MCDI worked and villages where they did not as my scoping study suggested that MCDI presence and interventions such as early burning may impact attitudes to environmental management and to fire use. The ecological aspects of my research (particularly chapter 3) are conducted at a broader scale: at 12 locations across the district (Figure 2.1). The stratified sampling design used by those who established the plots (McNicol et al., 2018) allows for larger-scale generalisations related to the impacts of fire on trees and long-term carbon storage dynamics in part of the miombo.

During my first full field season in Kilwa from September until November 2018, two weeks of pilot interviews (outside of the main study villages) and visits to the community forests led me to realise that these impacts would be difficult to measure independently: prescribed burning is one of many interventions used to protect community forests, and the pattern and timing of burning varies between villages.

My first field season therefore began with me asking questions about prescribed burning, and in the process learning that fire use outside of protected areas (chapter 4) and the impacts of those fires on wellbeing (chapter 5) were an interesting and understudied area of research in miombo woodlands, which I chose to focus on. Further questions emerged during the analysis of field data and informed my plans for data collection in the final field season from September until November 2019, particularly chapters 3 and 4. At this stage I also decided that I wanted to include landscape-level and long-term data to inform my understanding of miombo degradation, and to explore the assumptions I had heard and read many times: that fires in the miombo are causing loss of trees. I took an opportunity to re-measure permanent sample plots in Kilwa, which formed the ecological grounding of my thesis (chapter 3).

My aim in this thesis is to combine bottom-up and top-down perspectives in order to triangulate and limit the partiality of the research findings (Nightingale, 2003, 2020; Rasmussen et al., 2016). The most direct mixing of methods comes in chapter 4 – which combines qualitative interview data with remote sensing. I also contextualised and triangulated the ecological data in chapter 3 with data from focus group discussions. Much of the overall integration of disciplines emerged from my experiences using multiple methods and is conveyed in the final chapter where I synthesise and discuss my findings. The thesis that results from this combining of methods and study scales of course remains limited in its scope. I do not assume that it is possible to generalise from this case study, but rather hope that it can point to further issues which deserve attention in miombo woodland research and fire management (Yin, 2003).

I give a brief outline of the main qualitative and quantitative data collection methods and the role of MCDI during fieldwork in the following section (2.3.3), with further details in the subsequent sections and in the relevant study chapters.

2.3.3 Fieldwork overview

While planning fieldwork, I was focused mainly on the aim of collecting ecological and social data; an overview of the methods used is given in Table 2.1. I built flexibility into my plans –

including contingency time and budget – so that I could modify my schedule and methods while I was away if I needed to, knowing that things were likely to go wrong. An important aspect of this was piloting my methods in 2017, and at the start of the main field seasons in 2018 and 2019 (Table 2.1; section 2.3.2).

Table 2.1 Overview of main data collection methods for this thesis.

Description of method	**Relevant chapter**
November 2017: two week scoping visit to Kilwa District, Tanzania. Time spent visiting permanent sample plots for woodland surveys, and conducting pilot interviews about fire use and prescribed burning.	(Piloting methods for chapters 3, 4 & 5)
September 2018: piloting interviews and focus group discussions in two villages (Likawage and Mbwemkuru, which are not main study villages).	(Piloting methods for chapters 4 & 5)
September–November 2018: twelve focus group discussions across six study villages, including participatory mapping exercises, exploring local wellbeing goals, and the impacts of fire on those goals.	Data reported in chapters 4 & 5
September–November 2018: three focus group discussions in each study village participating in community-based forest management, exploring the process and impacts of prescribed burning.	Data reported in chapters 4 & 5
September–November 2018: 112 semi-structured interviews across the six study villages exploring causes and consequences of fire. Four of the interviews in each village were conducted as walking interviews to explore locations where there had been recent fire.	Data reported in chapters 4 & 5
September 2019: reporting findings from previous field season and piloting ranking exercises in two villages. Piloting woodland survey methods on one plot.	(Piloting methods for chapters 3, 4 & 5)
September–November 2019: Resurvey of 300 x 300 m woodland plots, first measured in 2010/2011.	Data reported in chapter 3
September–November 2019: twelve focus group discussions across six study villages, to report and validate major findings from previous field season, triangulate woodland survey data, and conduct ranking exercises.	Data reported in chapters 3, 4 & 5

Remote sensing analysis of the MODIS Burned Area data product (MCD64A1), completed largely by Christopher Andrews (for chapter 4). I extracted fire frequencies for chapter 3.	Data reported in chapters 3 & 4

Due to difficulties communicating with anyone outside of the study communities (in most villages there was no phone signal), I had little contact with my supervisors while on fieldwork, and few opportunities to refer to academic papers, textbooks, or other resources for guidance. So, this was a time when I particularly felt both the pressure and the privilege of truly owning my research. Aside from data collection, I further developed my research aims during fieldwork, narrowing down not just those which would fill gaps in academic literature, but those that were relevant to my study site and the communities there, and modified my methods. I reflected critically on the work I was doing throughout, as I wanted to maximise the use of my limited time.

In particular, I moved away from my idea of studying prescribed burning in detail during piloting stages of my fieldwork. This was due to both difficulties in designing a study which could determine the ecological impacts of prescribed burning in isolation (there are several interventions in the community forests besides prescribed burning), and because I learned that other local fire management practices played a far bigger role in peoples' lives (see section 2.3.2 for more on this decision). This pushed me to focus instead on understanding why people set fires, how intentions impact the resulting fire regime, and how fires impact wellbeing.

I worked with MCDI throughout fieldwork. I employed MCDI staff during my pilot study in 2017 and during the ecological fieldwork in 2019. MCDI also provided administrative and bureaucratic support throughout, for example helping me to chase my research application to the Tanzania Commission for Science and Technology, and gain temporary research permits so that I was able to continue working while I waited for research permission to be granted. I paid MCDI an administrative fee for this support. MCDI did not contribute substantially to the findings reported in my analysis chapters. Some staff were asked about the process and impacts of prescribed burning in order to triangulate reports from respondents in the villages. The perspectives of MCDI staff on the impacts of prescribed burning is reported in chapter 4.

As I wanted to establish whether MCDI's activities influenced perspectives towards fire use, I made the decision ahead of social science fieldwork in 2018 that I would hire a co-researcher/translator who was not known to villagers as a representative of MCDI. I hired Mercy Mgaya, who had never previously worked with MCDI or in Kilwa, to work with me on the study at the beginning of the 2018 field season. We were not independent of MCDI because, in order to formalise her employment and salary (and create future opportunities to work with the organisation), Mercy was employed by MCDI at the time I hired her. Her salary was paid by my research budget. However, Mercy had not been involved in any other activities delivered by MCDI, such as prescribed burning. We felt that this distance from MCDI's activities, in addition to a clear explanation of our research aims, was sufficient to encourage honest discussion about any impacts of prescribed burning and MCDI's other work. I elaborate on how we explained our connection with MCDI to research participants in section 2.3.5.

As well as collecting data, I aimed to mitigate the extractive nature of traditional academic research (Gaudry 2011) by sharing my findings with research participants. Initial findings were shared during focus group discussions in 2019. I had wished to return to Kilwa to share further findings but was unable to due to the Covid-19 pandemic. I have periodically updated MCDI on the progress of the research and its main findings.

2.3.4 Quantitative data collection and analysis

Chapter 3 uses mostly quantitative data from woodland surveys. The plots surveyed were established and initially measured by Iain McNicol and colleagues, including several employees from MCDI. See McNicol et al. (2018) for details. In summary: plots were established at 25 locations throughout Kilwa District between October 2010 and October 2011. Plot location was stratified by three vegetation types: 1) grass-dominated savanna with few trees, 2) savanna woodland with a mix of trees and grasses, and 3) closed canopy forest with no grass cover. Vegetation cover was assessed using Landsat 5 data and 300 in situ visual assessments. Plots were located randomly along road and track networks for access, with a 1-km buffer from tracks. At each site, one 9-ha (300 × 300 m) large sample plot (LSP) was established where trees ≥40 cm diameter were surveyed, with a centrally nested 1-ha (100 × 100 m) permanent sample plot (PSP) where trees ≥5 cm diameter were surveyed.

Between September and November 2019, I led the resurvey of the LSPs, returning to as many plots as possible within budget and time constraints, prioritising the miombo woodland plots. In total 14 LSPs were resurveyed. The rationale for focusing on the LSPs was threefold. First, in contrast with the PSPs, the LSPs had never been resurveyed and there had been little previous analysis of data from these plots. Second, large diameter trees disproportionately influence woodland structure, functioning and services – not least, aboveground carbon (AGC) storage (Lutz et al., 2018) with ≥40 cm diameter individuals making up just 2.6 ± 2.2% of all stems in Kilwa's PSPs but containing 32 ± 18% of AGC (McNicol et al., 2018). Yet, large trees tend to be understudied because they are relatively rare compared to smaller trees, and larger plots are required to capture sufficient sample sizes for data analysis. Finally, large trees are often assumed to be resilient to fire, but this has been poorly studied in inhabited landscapes.

In total, ~1900 stems were measured, tagged and geolocated in 2019 with two plots and around ~200 trees excluded from the analysis *post hoc*. At various points, Mercy Mgaya, Issa Abdulhamani, Erick Shallua, Gilbert Alex, Dactuce Ngenje, Emanuel Mlimitho, and Achsah Ezekiel were part of the field team. Two field workers took measurements while a local botanist, Abdalla Mpula, led species identification. I recorded information for each measured tree under its local species name. A list of local species and their corresponding Latin names developed during the previous survey effort was generously provided by Iain McNicol. As different botanists may use different local species names, I verified and augmented this list for species identified during the resurvey using voucher specimens and reference guides (Coates Palgrave, 2002; van Wyk & van Wyk, 2013). Further details on the data collected and analysis are given in chapter 3.

Chapter 4 is informed by remote sensing data analysed by Christopher Andrews; details of Christopher's analysis is given in the chapter.

2.3.5 Qualitative data collection and analysis

Much of the data underlying chapters 4 and 5 of this thesis comes from semi-structured interviews and focus group discussions conducted in English by myself, translated into Swahili with additional questions asked by Mercy Mgaya. More details on the content of the interviews and discussions are given in the relevant chapters; here I explain my rationale behind the overall approach and reflect on the role myself and Mercy played in data collection and analysis.

Perspectives on degradation in the study villages are complex and informed by personal experience and education, for example interactions with conservation groups (section 2.2). I learned quickly during pilot work in 2017 (when I worked with an MCDI employee, Iddi Hamisi, who helped to organise interviews and acted as a translator) that fire use is a sensitive area of enquiry, particularly in relation to some activities like hunting. The likely reasons for this were later discussed with some respondents who suggested this was due to fear of recrimination from neighbours or from us, the researchers, who may be thought to represent the district authority. It was therefore not practical to implement random sampling design and use e.g. surveys to gather quantitative data; I felt that such an approach would have missed important understandings, particularly surrounding the nuances of fire impacts. I also felt that a rigorous quantitative survey design would trade-off with opportunities to build trust and access interviewees willing to discuss sensitive topics such as hunting and other uses of fire, and so I decided to collect only qualitative interview data.

I used a hybrid approach to qualitative data collection and thematic analysis, drawing on grounded theory (Charmaz, 2006) and using both inductive and deductive methods. During the pilot phases of my research, interviews were unstructured and unguided by particular theories. Themes that emerged during my analysis of the pilot data shaped the research questions at this stage, and the approach to data collection upon return to the study villages.

At the beginning of the first main field season in 2018, I hired Mercy Mgaya to work with me on the study (initially, focusing on the qualitative aspects though Mercy was also part of the field team collecting ecological data in 2019). Mercy and I were both new to qualitative data collection before this research, and discussed our approach at length during fieldwork. Starting from the point of my research aims underpinned by themes that emerged during the pilot work, my understanding of academic best practices, and Mercy's knowledge of social structures in Tanzanian villages, together we adapted interview methods and topics based on the experience of further piloting of methods and emerging findings.

We selected respondents using purposive sampling based on livelihood activities and other characteristics such as gender and involvement in village management, to gather a range of perspectives both within and between individual villages. Men are the primary users of fire for several livelihood activities and therefore had greater control than women over the information conveyed about these activities (Herod, 1993). However, we sought as many female perspectives as possible, and in total men made up 62% of respondents across all interviews. In total, five interviews were conducted with members of the Sukuma tribe. No members of the Sukuma tribe were part of the focus group discussions because typically members of this tribe are less integrated in village affairs, and there are some difficult relations between Sukuma people and others in the village (see details in section 2.2).

Semi-structured interviews and focus group discussions were used to understand complexities, consensus and contradictions. I led the questions during interviews, while Mercy translated between English and Swahili, and asked follow-up questions. Early parts of interviews and focus group discussions were kept open, so there was space for new ideas to continue emerging. We used ranking exercises and participatory mapping (see example map in Appendix 1) during focus groups, which helped shift away from a purely question-answer dynamic and instead facilitate discussions between respondents. This similarly allowed new ideas – led by the respondents rather than us the researchers – to emerge. Later in interviews and focus group discussions, we asked more structured questions guided by theory and emerging findings (section 2.4). I made notes on a tablet throughout interviews and focus groups, which I discussed with Mercy at the end of each day to confirm that the notes were accurate and complete. We identified further research questions based on the interview findings, selected appropriate respondents, and adapted our interview questions, to answer them.

Participant observation was also an important component of data collection. Fieldwork was during the fire season, due to helpful coincidence more than planning: I planned fieldwork during the late dry season because access to villages via dirt roads, which get washed out in heavy rain, is far easier and because interviewees are less busy with farm work at this time of year. During our four walking interviews in each village (two with men and two with women) in particular, we observed where and how fire was managed. We gained some crucial insights through this, for example by seeing the fire breaks burned around agricultural fields we learned that people often exaggerated their width (often indicating that they were several metres wide when, in fact, they were usually less than 1 m). More broadly, this helped to develop our understanding of how some people presented information to us: often emphasising the negative aspects of fire, and aiming to appear to be ‘good’ citizens or environmentalists by using fire carefully and controlling its spread.

Data were collected until the point at which new insights related to the research questions stopped emerging (i.e. theoretical saturation was reached) (Charmaz, 2006; Bryman, 2012). For example, we interviewed hunters in all villages possible, and until we understood the nature of fire use in hunting.

I recorded interviews with the consent of participants. Due to the large volume of resulting data and the nature and aims of the research, I did not transcribe all interviews in full but instead referred to recordings when necessary to supplement analysis of the detailed interview notes. For thematic analysis following my first and second field seasons I was guided by the practical approach described by Swain (2018). Over several rounds of re-reading and re-coding interviews, I searched for themes fitting a priori codes dictated by theory, while also allowing a posteriori codes to emerge from the data. As Swain (2018, p. 5) states, this approach meant that “theory was both a precursor to, and an outcome of, the data analysis”. The capability approach, theories on multidimensional wellbeing, and the ecosystem services framework underpinned the more deductive aspects of the research and are introduced later in this section.

Ranking exercises were used to contextualise interview data and quantify some of the key findings of Chapter 4. Informal discussions and observations were used to verify information and prompt new queries.

2.3.6 Positionality and ethics

Reflections on my own privileged position as a white British student conducting research in rural Tanzania have been at the forefront of my mind at various stages of this research, never more so than during fieldwork. The opportunity to conduct this research was afforded to me partly due to past and current inequalities, including those resulting from the colonial history between my own home country and Tanzania. Research ethics related to potential power imbalances between myself, my research partner Mercy Mgaya, and respondents, therefore required particular attention.

Mercy and I, both university-educated females, worked together throughout the fieldwork. Mercy is Tanzanian and from a city, but has also spent time living in villages in northern Tanzania. Neither of us had worked in Kilwa prior to this research. We were both therefore outsiders to the villages we worked in, but to different degrees and in some different ways (Dwyer & Buckle, 2009). Our outsider status impacted how we were perceived in the study villages. As two women, locals often expressed concern for our safety and made efforts to keep us safe in their villages, in one case even escorting us to interviews with Sukuma people due to fears associated with this tribe (we were treated kindly, or at worst disinterestedly, by all the Sukuma people we met). Often we were seen as teachers or potential financial donors. Several of the villages we worked in have experience of outsiders from NGOs providing environmental education or donations, so these perceptions were hardly surprising.

We tried to minimise perceived differences between ourselves and villagers while also discussing our own life experiences openly, in order to show respect and build trust. For example, many commented that they were happy to see us using public transport instead of the private cars they typically saw outsiders traveling in. We ate with local people and spent our days chatting to them. I conversed in very limited Swahili when I could, and we often talked with local people about their lives and answered questions about ours, finding commonalities and connection with the people we spoke to. We introduced ourselves and answered questions at a village meeting upon arrival in each village, to show respect and explain our research. There were far fewer language (apart from the odd word in a local language) and cultural barriers between Mercy and the villagers. Mercy garnered respect, laughter and friendship wherever we went and was undoubtedly a major reason for our being welcomed warmly in all the villages.

We tried to reduce the likelihood of people feeling coerced into participating in any part of our research through clear and friendly communication to gain genuine informed consent prior to any interview and to ensure that respondents felt comfortable with the direction of discussions. We introduced ourselves and the purposes of our research, giving respondents the opportunity to ask questions or choose not to participate if they so wished. We explained that we weren’t looking for ‘right’ or ‘wrong’ answers, but were there to learn what people really think and feel. Interview topics were flexible, and dependent on the areas in which respondents showed particular expertise and interest. Fire use is a sensitive area of enquiry in the study villages, and if respondents were uncomfortable or unsure, the conversation was steered in another direction.

One aspect of our identities we had to explain particularly clearly. Much of the admin and logistics of fieldwork were organised through MCDI and, while Mercy had never previously worked with MCDI, she was employed by the organisation at the start of this study to formalise her employment and salary, which was paid by my research budget. Therefore, while we explained that we were not in the study villages in order to represent the interests of MCDI – we were merely there for research – we had connections with the NGO. We explained that while we aimed to learn from a variety of perspectives in the study villages and hoped to publish major findings and share them with MCDI, all respondents would remain anonymous.

We believe that our efforts helped to combat misunderstandings about who we were (i.e. not authorities, law-makers or educators) and reduced the likelihood of different people telling us what they saw as ‘important’, problems we might be able to influence, or what we might want to hear. However, being outsiders created additional hurdles for the research such as our limited knowledge of local context. For example, when discussing prescribed burning, we would initially use the Swahili term *ubabuaji*. However, we learned while piloting our interviews that often there was another local term for *ubabuaji* which varied between villages, and many people had never heard of *ubabuaji*. We had to work hard to understand local meanings like this, to make sure we weren’t asking questions based on our own assumptions, to explain our understanding of concepts to villagers, as well as listening to theirs. Gross-Camp (2017) writes that in Tanzania, there is pressure to present to outsiders that modern and scientific understandings of e.g. biophysical processes are better than traditional understandings and ritual. My awareness of potential bias or misrepresentation in our data such as this informed my interpretation of emerging social data.

While we think that our efforts made for a more ethical intrusion on village life and were beneficial for our research, there are still likely interesting social dynamics which an insider would have observed, but which we as outsiders did not. However, in other cases our outsider status likely encouraged interviewees to tell us information they would likely be reluctant to share with a neighbour: such as when they have caused harmful fires in the village, and when they collected resources from the community forests without permission.

All respondents were thanked for their time with a payment of 5000 TZS Tanzanian Shillings (~2 US$) per interview, following the advice of MCDI staff and a precedent set by researchers who had previously worked in the study area. The study was approved by the University of Edinburgh School of Geosciences Ethics Committee.

2.4 Key concepts and theories

2.4.1 Ecosystem services and disservices

In their broadest conceptualisation, the normative assumptions underlying this thesis are that ecosystems (here, miombo woodlands) provide benefits to people and that humans should manage ecosystems to maximise those benefits and/or minimise harms. Evidence derived from research can help us better manage ecosystems to this aim. Nature's benefits are commonly referred to as 'ecosystem services' in academic literature (Ehrlich & Ehrlich, 1981). In the early stages of my PhD, I read widely around human-nature interactions and ecosystem services, including relevant frameworks and their critiques. Much of the thinking behind this thesis is rooted in this reading and in my pilot interviews conducted in 2017 and 2018 (Table 2.1).

The most influential ecosystem services framework was developed as part of the Millennium Ecosystem Assessment (MA, 2003), and has been subsequently modified and critiqued by numerous authors. This framework, which built on decades of previous research (Baveye et al., 2013), outlines three categories of ecosystem service which directly impact people: provisioning, regulating and cultural services. A fourth category of ecosystem service – supporting services – sustains services in the other three categories. The framework indicates multiple dimensions of human wellbeing which interact with these services (Figure 2.3).

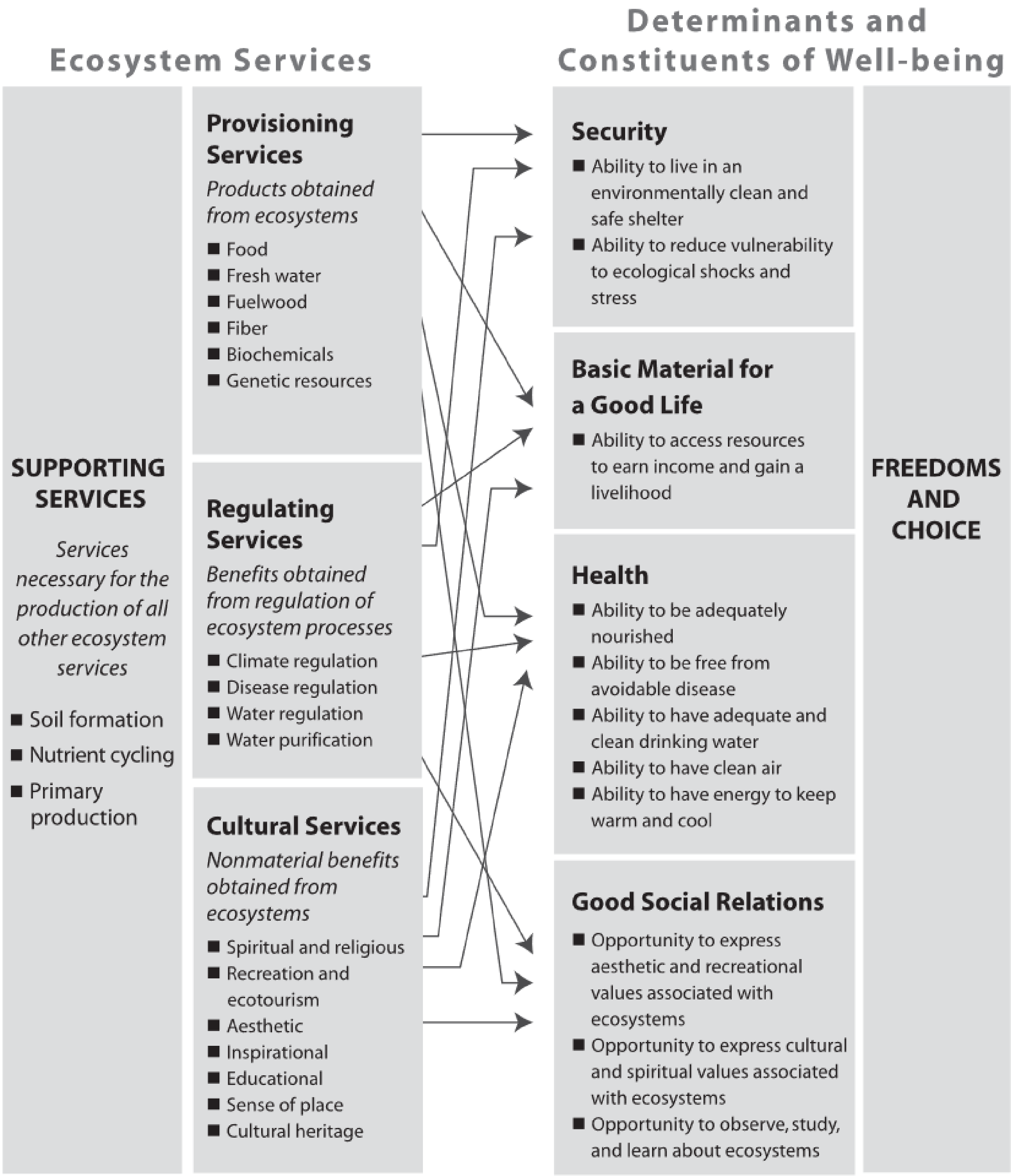


Figure 2.3 Ecosystem services and their links to human wellbeing: a framework from the Millennium Ecosystem Assessment (MA, 2003).

Critics of this framework point out that there have been few empirical studies exploring the assumption that ecosystem services are linked to human wellbeing (Cruz-Garcia et al., 2017) and that researchers tend to neglect complexities surrounding ecosystem services such as the existence of ecosystem disservices, synergies and trade-offs, and links to non-monetary aspects of human wellbeing (Raudsepp-Hearne et al., 2010; Dunn, 2010; Lele, 2013; Suich et al., 2015; Shackleton et al., 2016). Other have found that this and related frameworks developed by experts do not necessarily align well with people's values (Maund et al. 2020). The tendency for researchers to overlook both the role that local communities play in ecosystem management and of indigenous and local knowledge has prompted the creation of modified versions of the ecosystem services framework which elevate the role of local knowledge (e.g. Comberti et al., 2015).

Nature's contributions to people (NCP) developed by researchers at the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2018) is the most prominent counter-concept and framework, put forward to replace ecosystem services. Defined as "all the contributions, both positive and negative, of living nature… to people's quality of life", NCP has at its heart culture, local knowledge, both benefits and harms from nature: aspects which have often been overlooked in ecosystem services research. However, critics argue that, over decades of research and policy, the ecosystem services concept has already developed to include these previously overlooked dimensions and NCP brings nothing new (Braat 2018; de Groot et al. 2018). A literature review agreed that NCP does not differ significantly from ecosystem services in some conceptual claims, however it found that NCP does offer a new framing of human-nature relationships in other ways, for example by giving greater prominence to non-western-scientific worldviews, for having less rigid NCP, and using more inclusive language and framing (Kadykalo et al., 2019)

My overall approach to this research focused on one ecosystem process – fire – and explored its causes and impact (Bennett et al., 2009). I used an ecosystem services framing, following the MA framework and its critiques, for several reasons. First, the language of ecosystem services, and the types of service in the MA framework, not only continues to be widely used by academics but has been implemented in the development of environmental policy internationally (for example, the concept is used by both the UNFCCC and CBD) and subsequently by environmental NGOs. It continues to be the dominant framework for discussing human-nature interactions in many of these realms. As I aimed to conduct research which could be used by a multidisciplinary audience to inform fire management practice, I wanted to align my terminology with that used by policymakers and academics from various disciplines.

Secondly, I was able to use ecosystem services framings in my research while benefiting from insights from decades of ecosystem services research and critiques, including those put forward by researchers developing alternative frameworks. I haven't used a particular ecosystem services framework rigidly: rather, I have drawn on ecosystem services insights which were most relevant to my study. Following e.g. Díaz et al. (2018) chapters 4 and 5 are strongly grounded in local knowledge and perspectives. This is the intentional outcome of my qualitative data collection and analysis, which was focused in rural communities, and was both deductive and inductive, allowing for new ideas and perspectives from respondents to emerge (section 2.3.5).

Following Comberti et al. (2015) amongst others, I have focused on both the flow of services from ecosystems to humans, as well as human 'services to ecosystems': studying the ways humans use fire and shape the overall fire regime in Kilwa (chapter 4), the impacts this has on ecosystem services provided by trees (chapter 3), and other ecosystem services including broader impacts on local wellbeing (chapter 5). I also research potential harms from fire (especially in chapters 3 and 5), addressing the common criticism that research has often failed to acknowledge the existence of ecosystem disservices (e.g. Lele, 2013; Suich et al., 2015). My choice to gather large amounts of qualitative data was driven partly by an aim to capture the complexities and nuances surrounding ecosystem services, disservices and fire. I aimed for a rich qualitative understanding, rather than a quantification of, for example, the monetary costs and benefits of fire, which has been a common approach in ecosystem services research.

Finally, I found during my pilot research that using categorisations of ecosystem services in the MA framework was a helpful tool to guide my interview questions. Initially I asked respondents general questions around benefits and harms from nature, and whether fire impacted these benefits and harms. In response, most spoke about a limited subset of the most commonly used natural resources, while other ecosystem services (for example medicinal plants and cultural values) were often overlooked. I did not apply an ecosystem service framework in a systematic way, but simply referred to the traditional categories of services (Figure 2.3) to prompt discussion with some respondents about other aspects of fire use and impacts, for example by asking about perceived impacts of fire on soils. While my findings on fire impacts using this method are incomplete, they are certainly richer for my having broadened the interview topics in this way.

In an ecosystem services framing, fire can be understood as a process which can deliver both services (Pausas & Keeley, 2019) and disservices (Sil et al., 2019). Identifying ways to manage fire regimes to maximise ecosystem services while minimising disservices is a goal in many fire-prone regions of the world (Colombaroli et al., 2019; Moore, 2019; Castro Rego et al., 2021). In Chapter 3 of this thesis, I focus on carbon storage as a regulating service and other services provided by trees in Kilwa. Chapters 4 and 5 focus on the ways that fire is used as an ecosystem management tool by local communities to maximise different services, for example agricultural land and rangelands for livestock, as well as the impacts that fire has more broadly on wellbeing (including disservices which negatively impact wellbeing).

2.4.2 Multidimensional wellbeing and the capability approach

Understanding wellbeing in the study communities was a major underpinning of this research. Learning more about wellbeing from the perspective of respondents generally – what people value, and what causes harms – enabled me to ask better interview questions and interpret findings in a way that was more relevant to local people, centring my research on their perspectives. I use an explicit wellbeing framing in Chapter 5, which implements Amartya Sen's capability approach (Sen 1979) and the World Bank's Voices of the Poor research and framework (Narayan et al., 2000).

Like ecosystem services research, studies of wellbeing often overlook nuances, with wellbeing frequently defined solely by income and assets, particularly in environmental-social research (Duraiappah, 2011; Lele, 2013; Suich et al., 2015). Increasingly, researchers have called for greater recognition of the multiple dimensions of wellbeing (Sen, 1999; Gough et al., 2007; McGregor, 2007). In the early months of my PhD I read around multidimensional wellbeing, aiming to identify both theories and methods which could help establish an understanding of multiple dimensions of wellbeing at my study site. Notably, I read much work from the Wellbeing in Developing Countries research group at the University of Bath (Gough and McGregor, 2007) and work from the School of International Development at the University of East Anglia (e.g. Dawson & Martin, 2015). In their conceptualisations of wellbeing these studies incorporated, for example, material components such as access to food and money, social components such as good relationships, and subjective desires.

I wanted to use focus groups to gauge general values and beliefs around what was needed to live well in my study communities (using the Swahili terms *ustawi*, meaning welfare and *hali ya maisha*, meaning conditions of life; see Appendix 2: Interview prompts for wellbeing focus group discussions and participatory mapping) (Abunge et al., 2013). I first asked broad questions such as: *How would you describe someone who has high wellbeing in your village? How about someone who has low wellbeing?* However I found during piloting in 2017 and 2018 (Table 2.1) that, like my experiences asking general questions around fire impacts (section 2.4.1), this resulted in limited responses, often focused solely on economic aspects of wellbeing. I chose to use a framework to guide further questions around more diverse aspects of wellbeing, to help overcome this issue.

I used the Voices of the Poor framework to structure some of the questions during focus group discussions. Unlike my use of the MA ecosystem services framework, I used this framework in a systematic way with every group, asking explicitly whether wellbeing is linked to the five dimensions of the framework: material goods; health/the body; social relations; security; freedom and choice (following the more general questions like those given above; Appendix 2). There were just 12 focus groups of this type – six with men and six with women, and I wanted to cover the same breadth of topics in each discussion to gain a richer understanding of multidimensional wellbeing across villages and genders, identifying areas of consensus and disagreement.

I chose to use the framework from Narayan et al. (2000) firstly because it was developed based on an extensive dataset: involving over 20 000 people from 23 countries. While it is a simple framework, it incorporates wellbeing dimensions highlighted in other literature (e.g. Gough and McGregor, 2007). Additionally, because the framework is simple, it was easy to integrate into focus group discussions without making discussions overly complicated or long. Finally, this framework was incorporated into the Millennium Ecosystem Assessment Framework exploring Ecosystem Services and Their Links to Human Wellbeing (the 'Determinants and Constituents of Human Wellbeing'; in Figure 2.3) and in this context as well as others, has therefore also been widely implemented in both research and policy.

During my analysis of the qualitative data on multidimensional wellbeing (chapter 5), I noted that emerging themes aligned with Amartya Sen's capability approach. In particular, the recurring theme of the importance of "moving up a stage in life" repeated by respondents, chimed with its emphasis on individual freedoms. In the capability approach, which has been further developed by Sen himself and others (e.g. Sen, 1979, 1993, 1999; Nussbaum, 2000), a good life is characterised by 'capabilities' i.e. real opportunities to pursue achievements ('functionings'), such as doing satisfying work, being healthy, being literate: a person doing what they want to do and being who they want to be (Robeyns, 2005). It therefore incorporates subjective wellbeing, dealing with humans as they are, in their circumstances (Rojas, 2007) and is concerned with each person's freedoms to lead a life they have reason to value (Robeyns, 2017).

My emerging findings also identified a range of complex impacts of fire on wellbeing – positive and negative, physical and psychological. The flexibility of the capability approach in its most basic form, which can be used to evaluate positive, negative or neutral functionings and capabilities and their interactions, offered a useful tool for evaluating these complexities (Suich et al., 2015). The approach has been used to understand wellbeing-nature interactions and their inherent complexity in multiple studies (e.g. Polishchuk & Rauschmayer, 2012; Daw et al., 2015; Sangha et al., 2015; Dawson & Martin, 2015). However, neither the capability approach nor other theories and frameworks of multidimensional wellbeing have been used to study the impacts of fire previously, so this offered a novel and useful tool for my research. The specific ways in which the capability approach and the Voices of the Poor research were used during data collection and analysis are further explained in chapter 5.

2.5 References

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Chapter 3. Fire reduces growth but does not elevate mortality of large trees in the miombo

Miombo woodland the day after a fire in Kilwa District, Tanzania (Ellie Wood, 2019).

Chapter 3. Fire reduces growth but does not elevate mortality of large trees in the miombo

3.1 Abstract

Degradation (loss of trees) threatens the global and local benefits provided by southern African miombo woodlands, such as carbon storage, biodiversity, and building materials for their rural inhabitants. These ecosystems have complex tree mortality and regrowth dynamics, therefore quantification of demographic rates and identification of their underlying drivers is crucial to inform sustainable management. This study explores an understudied aspect of degradation in the miombo: how fire affects the dynamics of large diameter trees, which disproportionately influence the carbon storage capacity, diversity, structure and functioning of wooded ecosystems. I report results from the resurvey of 9-hectare sample plots and ~1700 large (≥40 cm) diameter stems, triangulated with focus group discussions in 12 villages in Kilwa District, south-eastern Tanzania. I find that aboveground carbon storage and diversity remained stable over 9 years, with carbon losses to mortality being offset by recruitment and stem growth. On average, large stems stored 10.9 ± 5.1 (SD) tC ha^{-1}. Mean annual mortality rate was 2.3 ± 1.0% while mean annual recruitment was 1.9 ± 0.6%. A multi-level linear regression estimated a mean diameter increment of 3.06 ± 0.19 (SEM) mm yr^{-1}, with wounding and increased fire frequency reducing growth rates. Annual burning reduced growth by 1.12 ± 0.43 (SEM) mm yr^{-1}. A binomial generalized linear regression estimated that wounding, but not fire, increased the odds ratio of mortality. These findings together challenge assumptions that large trees are unaffected by fires in the miombo, but show that they are resilient to the current fire regime.

3.2 Introduction

Loss of tree cover via deforestation and degradation threatens ecosystem services provided by woodlands and forests the world over (MA, 2005; Hosonuma et al., 2012; Hansen et al., 2013; Lewis et al., 2015). These processes have received widespread academic attention, particularly in relation to the potential for avoided deforestation and degradation (as well as reforestation and, controversially, afforestation) to enhance carbon storage and mitigate climate change (Houghton, 2012; Baccini et al., 2017; Bastin et al., 2019). However, as many authors have pointed out, such dynamics are highly specific to local circumstances and global analyses can mask nuances, or even entirely pervert the best way to manage different ecosystems (Veldman et al., 2015, 2019; Hansen et al., 2019; Wyborn & Evans, 2021). This is particularly true considering the multiplicity of ways that ecosystems can be valued for different purposes, benefits, or services (Daw et al., 2015; Ryan et al., 2016; Pritchard et al., 2019).

In the miombo woodlands of southern Africa, degradation (loss of trees from a patch of woodland) is the dominant process by which trees are lost from the landscape (as opposed to deforestation – complete conversion of the woodland patch), but these losses can be offset by woodland regrowth (McNicol et al., 2018). Processes like fire and herbivory which result in tree mortality here are potential drivers of degradation and simultaneously crucial to maintaining miombo woodlands – which are disturbance-driven ecosystems (Ribeiro et al., 2020). A recent review found that tree biomass varies widely across miombo woodlands, with aboveground carbon stocks reported as ranging between 1.3 and 95.7 tC ha^{-1} (Gumbo et al., 2018), reflecting the dynamic nature of the region and the diversity of ecosystem structures here. However, large-scale and long-term woodland monitoring to elucidate spatial and temporal dynamics across a diversity of miombo systems, and the factors dictating them, is limited compared to other ecosystems (McMahon et al., 2019; SEOSAW, 2020).

The exact nature of the fire regime affects species composition, woody biomass and carbon emissions in miombo woodlands (Ribeiro et al., 2021). At the extremes of possible outcomes, experimental evidence and modelling suggests that annual burning could lead to the conversion of woodlands to grasslands (Trapnell, 1959; Ryan & Williams, 2011) while total fire suppression could lead to woody encroachment (Bond & Keeley, 2005; Saito et al., 2014). Neither of these outcomes are desirable to sustainably manage the miombo and the ecosystem services they provide to global and local populations (Jew et al., 2016; Luvuno et al., 2018). Therefore, establishing the long-term impacts of real-life fire regimes (rather than experimentally manipulated ones) on the miombo is an important but understudied area of research.

Large-diameter trees are keystone structures in forests and woodlands, disproportionately influencing biodiversity, ecosystem processes and services, not least carbon storage as a regulating service (Lindner, 2010; Lindenmayer et al., 2012; Lutz et al., 2018; Bastin et al., 2018). In Kilwa District, Tanzania (the field site of the current study) for example, trees with a diameter of ≥40 cm comprise just 2.6 ± 2.2% of all trees ≥5 cm, but store 32 ± 18% of aboveground carbon (McNicol et al., 2018). Large diameter trees also provide timbers for local and commercial logging, and most miombo species are able to resprout after being cut (Grundy, 1995). However, resprouting ability depends on a number of factors, such as stump height and stem diameter at the time of cutting (Luoga et al., 2004). Additionally, resprouting seedlings are vulnerable to fire and relatively few are subsequently recruited into larger size classes. Overharvesting can entirely remove stems in large size classes from some areas (Jew et al., 2016).

Despite their importance, large trees are understudied worldwide and most woodland and forest monitoring methods which do not focus on large trees are insufficient to gather reliable data on them, and the threats they may face. Large trees are relatively rare, so bigger sample plots are required to gather sufficient sample sizes for useful estimates of demographic rates and to capture heterogeneity in their spatial distribution (McNicol et al., 2018). Large trees may also face different threats to smaller trees; for example, in inhabited African landscapes, they can be more vulnerable to removal by humans, but less vulnerable to elephant damage (Lindenmayer et al., 2012; Tripathi et al., 2019; Muvengwi et al., 2020), which may be missed in smaller plots. Large diameter trees are often assumed to be more resilient to fire damage than smaller stems, but experimental and field evidence show that adult stems can be vulnerable to fire (Ribeiro et al., 2008; Ryan & Williams, 2011). However, no studies have focused on the impacts of fire on large diameter miombo trees.

In this study, I report on the resurvey of 9-hectare permanent sample plots established in Kilwa District, south-eastern Tanzania in order to elucidate key demographic rates and changes to aboveground carbon storage in stems of ≥40 cm diameter, over ~9 years. I also present a limited dataset, obtained from focus group discussions conducted in nearby villages, to establish local uses of large diameter trees and perceptions of how their availability may have changed over time. I aimed to enhance understanding of an understudied aspect of miombo degradation, focusing on large diameter stems and their potential threats. In particular I aimed to understand how the current fire regime impacts large trees relative to other potential drivers of degradation. I asked the following questions:

1. How has the floristic diversity of large stems changed over 9 years?
2. How has aboveground carbon storage changed over this time?
3. What are the mortality, recruitment and growth rates of large stems?
4. How does fire influence stem growth and mortality?

3.3 Materials and methods

3.3.1 Study site and overview of methods

The study site was Kilwa District, in the Lindi Region of south-eastern Tanzania (sections 1.6 & 2.2). Background on the quantitative and qualitative methods used are given in section 2.3 of this thesis, with specific methods detailed below.

3.3.2 Woodland inventory

Fourteen 300 x 300 m plots in Kilwa District, established and first surveyed between October 2010 and October 2011 (see section 2.3.4 for details), were remeasured between September and November 2019. Stems and stumps with a diameter of ≥40 cm were measured, tagged and geolocated during both surveys, recording: species, diameter (at breast height, DBH, taken at 1.3 m for stems; taken near the top of stumps at around 0.3 m), whether the stem was alive or dead, standing or fallen. Stem mortality was noted if the stem was either totally dead (i.e. whole tree mortality had occurred), or topkilled (with or without resprouting). Diameter was the average of two calliper measurements taken at right angles during the first survey, and was taken with a tape measure during the second survey.

During the resurvey in 2019, additional qualitative data on stem damage (if the stem was broken, if bracket fungus was present and if the cambium was exposed) and mortality (mode of death and potential causes) were collected. Recruits were stems and stumps with a DBH of ≥40 cm which had not been recorded in the first survey; these were tagged and measured during the resurvey.

Two plots were excluded from analyses post hoc as the species composition and structure of the plots did not represent miombo woodland. The locations of the 12 plots included in the final analysis are shown in Figure 2.1.

Stump diameters were adjusted post hoc according to the equation developed by Luoga et al. (2002, 2004): DBH=−1.003+0.87 BD (R^2=0.98) (DBH=diameter at breast height; BD=basal diameter); this equation was developed based on multiple species in a miombo woodland in Morogoro, eastern Tanzania. Any stumps not meeting the ≥40 cm diameter threshold following this adjustment were subsequently excluded from analyses (n=47). As many old stumps have a reduced diameter due to bark loss, I expect that this is likely to marginally underestimate the number of stumps in the size class of interest.

Data cleaning and all statistical analyses were performed in R (R Core Team, 2014), with figures produced using the ggplot2 package (Wickham, 2016). ± indicates standard deviation unless otherwise stated.

3.3.3 Plot floristics

I used the species name or genus where known to assess floristic composition and alpha diversity (species richness, Shannon index and Pielou's evenness) of the plots, using the vegan package in R (Oksanen et al., 2020). Local names were used for five morphospecies which could not be identified. Changes to alpha diversity indices between surveys were compared with Wilcoxon Signed-Rank Tests (Pelletier et al., 2018).

3.3.4 Calculating mortality, recruitment and growth rates

Mortality (M) and recruitment (R) rates were calculated relative to the number of living stems in the first survey following Gomes et al. (2003):

$$M = \{1 - [(N_0 - m)/N_0]^{\frac{1}{\Delta t}}\} \text{ x } 100$$

$$R = \{[(N_0 + r)/N_0]^{\frac{1}{\Delta t}} - 1\} \text{ x } 100$$

Where N_0 = number of living stems in the first survey, m = number of stems which died between surveys (were recorded as alive in the first survey and dead in the second survey), r = number of stems recruited between surveys (were not recorded during the first survey but were alive and above the DBH threshold during the second survey), and Δt = time between surveys (intersurvey period). Intersurvey period was 8 or 9 years, depending on whether the plot was first measured in 2010 or 2011. Stem turnover (the rate at which stems are replaced) was calculated as the mean of stem mortality and recruitment (Phillips & Gentry, 1994).

Diameter mean annual increment (dMAI) – the average increase in stem diameter per year of each stem that was alive in both surveys – was estimated based on the intersurvey period. This is a self-scaling measure of growth, with a given diameter increment representing a greater gain in biomass in larger stems (Bowman et al., 2013).

3.3.5 Modelling the determinants of stem growth and mortality

To understand the drivers of the demographic rates regression models were fit using the lme4 package in R (Bates et al., 2015). Growth rate was modelled in a multi-level linear regression with dMAI as the response variable. Stems were excluded from the model if the point of measurement had changed between inventories (n=40) and if data were missing from one of the inventories (n=1). Two outliers: with unrealistically high (52.6 mm yr^{-1}) and low (-50.8 mm $yr^{-}1$) growth rates put down to measurement errors, were also excluded. The resulting dataset retained stems with negative growth (n=45), which is assumed to be real stem shrinkage.

A binomial generalized linear regression with a logit link was used to model factors associated with mortality. Only stems that were alive during the first were included in the model (i.e. stems that were dead during the first survey and dead recruits were excluded), with a binary mortality (died / survived to the second survey) response variable. Stems were excluded if they were recorded as alive during the first survey but their initial diameter measurement was missing (n=8).

Variables which previous studies have shown to correlate with stem growth and mortality were included in candidate models. Continuous numeric parameters were scaled by subtracting the sample mean and dividing by two standard deviations, to aid comparisons with binary parameters (Gelman et al., 2020). Models were compared with an ANOVA, and evaluated using the Bayesian Information Criterion (Chakrabarti & Ghosh, 2011). The parameters used in the final models are given in Table 3.1.

Table 3.1 Parameters included in stem growth and mortality models based on data for stems ≥40 cm diameter surveyed in Kilwa District, Tanzania. Stems were first surveyed during 2010/2011 and subsequently surveyed during 2019.

Parameter	Model inclusion	Description
Initial stem diameter	Fixed effect in the growth and mortality models	DBH of each stem as measured during the first survey.
Probability of plot burn	Fixed effect in the growth and mortality models	The MODIS Burned Area data product (MCD64A1) was processed in QGIS version 3.10.10 (QGIS.org, 2022) to count the number of years that each plot burned from the year of first survey up until and including the year of the second survey (*t*). The probability of burn was then calculated by dividing by *t* for each plot.
Damage recorded during the first survey	Fixed effect in the mortality model	All notes made during the first survey were reviewed for comments about stem damage, and used to make a binary variable indicating whether a stem had been recorded as damaged based on key words such as “wound”, “shedding bark”, “hollow”, “axe”.
Cambium exposure recorded during the second survey	Fixed effect in the growth model	A binary variable indicating whether bark had been lost from any part of the stem below 2 m off the ground.
Intersurvey period	Fixed effect in the growth and mortality models	A binary variable indicating whether time between surveys was 8 (plots first surveyed in 2011) or 9 (plots first surveyed in 2010) years.
Plot	Random effect in the growth and mortality models	Plot ID; included to account for within-plot correlations driving stem responses.
Species	Random effect in the growth and mortality models	Morphospecies; included to account for within-species correlations driving stem responses.

3.3.6 Carbon storage estimates

The aboveground woody biomass (AGB) of each living stem recorded during the first survey and the second survey was estimated using DBH measures and the allometric equation developed by Chave et al. (2014), with calculations performed using the BIOMASS package in R (Réjou-Méchain et al., 2017). There were some alive stems with missing diameter data from the first (n=8) and second surveys (n=3). For these stems, the missing DBH measurements were estimated based on the dMAI estimated by the growth model, adjusted for the intersurvey period. AGB was assumed to be 47% carbon for aboveground carbon storage (AGC) estimates (IPCC, 2006). Change in AGC per hectare between surveys was compared with paired t-tests after confirming the assumption that the paired differences were roughly normally distributed (Pelletier et al., 2018).

3.3.7 Focus group triangulation

During the 2019 woodland inventory period, focus group discussions in six study villages (Figure 2.1) were held, lasting between two and three hours with two groups of 10 men and women in each village (one group of members from village committees and one with non-committee members). These discussions were primarily focused on validating social science data on the causes and consequences of fire, as part of the wider research contained in this thesis. During these discussions I also asked respondents about some of the uses of trees (particularly large trees), how trees are selected and harvested, whether the availability of useful trees had changed over time, and the impacts of fire on woodland vegetation, in order to gather contextual data and triangulate (validate) results from the woodland surveys (Nightingale, 2020).

I did not validate the local species names used by respondents against our survey data (i.e. to check whether respondents used the same name for a given species as the study botanist did). As a given species may have multiple local names, or the same local name may be used for several species, there may be some mismatches between the local names given by respondents and the botanist. However, I think this is unlikely to be a significant issue here for two reasons. First, the study botanist identified known synonyms for local species, and as a Kilwa resident he is likely to know many of the local species names used by respondents. Second, as the number of different species discussed were few but each was widely used, and as most of the same local names were given in different villages, it is likely that respondents were referring to the same species when using a given local name. In cases where the local name mentioned was not present in the woodland plots, technical reports mentioning the local name were checked for the best guess of the Latin species.

NVivo 12 (QSR International, 2018) was used to thematically analyse interview notes.

3.4 Results

3.4.1 Comparing floristic diversity between surveys

In total, 12 plots and 1693 stems and stumps were included in the final analyses, with 45 morphospecies identified across both surveys and one stump which could not be identified in either survey. One species (an unidentified *Combretum* species known as *mtopilibowile*) was found only once, as a single dead stem on P10 in the first survey. Living stems were therefore represented by 44 different species: 42 of which were identified in the first survey and 43 of which were identified in the second. The dominant species were the miombo species: *Brachystegia boehmii*, *Brachystegia spiciformis* and *Julbernadia globiflora*, making up more than 55% of all living stems across all plots in both years (Table 3.2).

Table 3.2 Abundance of living stems ≥40 cm diameter surveyed in Kilwa District, Tanzania. Results are shown from the first survey of the plots (2010/2011) and the second survey (2019).

Species	Abundance across all plots		% stems across all plots	
	First survey	Second survey	First survey	Second survey
Brachystegia boehmii	282	252	21.6%	19.7%
Julbernardia globiflora	276	210	21.1%	16.4%
Brachystegia spiciformis	263	270	20.1%	21.1%
Burkea africana	72	82	5.5%	6.4%
Pterocarpus angolensis	58	52	4.4%	4.1%
Aganope stuhlmannii	46	55	3.5%	4.3%
Mimusops sp.1	35	40	2.7%	3.1%
Tamarindus indica	32	35	2.5%	2.7%
Strychnos madagascariensis	30	42	2.3%	3.3%
Amblygonocarpus andogenesis	26	27	2.0%	2.1%
Entada abyssinica	22	20	1.7%	1.6%
Millettia stuhlmannii	17	19	1.3%	1.5%
Combretum binderianum	16	21	1.2%	1.6%
Sclerocarya birrea	15	14	1.1%	1.1%
Boscia salicifolia	14	16	1.1%	1.3%
Mimusops sp.2	11	11	0.8%	0.9%
Terminalia myrtifolia	11	7	0.8%	0.5%
Afzelia quanzensis	9	11	0.7%	0.9%
Pseudolachnostylis maprouneifolia	9	16	0.7%	1.3%
Dalbergia melanoxylon	8	15	0.6%	1.2%
Lamprothamnus zanguebaricus	7	8	0.5%	0.6%
Msakala	6	7	0.5%	0.5%
Mcherenje	5	5	0.4%	0.4%
Sterculia africana	5	3	0.4%	0.2%
Mmangangwaru	3	3	0.2%	0.2%
Mnakapweo	3	3	0.2%	0.2%
Senegalia nigrescens	3	2	0.2%	0.2%
Vachellia robusta	3	5	0.2%	0.4%

Diospyros sp.2	2	2	0.2%	0.2%
Kigelia africa	2	2	0.2%	0.2%
Lannea schweinfurthii var. stuhlmannii	2	4	0.2%	0.3%
Terminalia sericea	2	4	0.2%	0.3%
Vitex donia	2	2	0.2%	0.2%
Albizia amara	1	1	0.1%	0.1%
Bobgunnia madagascariensis	1	0	0.1%	0.0%
Cassia abbreviata	1	2	0.1%	0.2%
Combretum sp.1	1	2	0.1%	0.2%
Diospyros mespiliformis	1	2	0.1%	0.2%
Mchepalibowile	1	1	0.1%	0.1%
Parinari curatellifolia	1	1	0.1%	0.1%
Strychnos usambariensis	1	2	0.1%	0.2%
Vitex payos	1	1	0.1%	0.1%
Ficus sp.1	0	1	0.0%	0.1%
Vachellia sieberia	0	1	0.0%	0.1%

Measures of alpha diversity at the plot level are summarised in Table 3.3. There was no statistically significant difference in plot species richness (V=16, p=0.45) or Pieolou's evenness (V=15, p=0.06) between surveys. There was a marginal, but statistically significant, increase in plot Shannon diversity (V=9, p=0.02) in the second survey compared to the first.

Table 3.3 Alpha diversity of living stems ≥40 cm diameter surveyed in Kilwa District, Tanzania. Results are shown for 12 plots first surveyed in 2010/2011 and subsequently surveyed in 2019. IP indicates the intersurvey period for each plot.

		N living stems		Species richness		Shannon index		Pielou's evenness	
Plot	**IP, years**	**First survey**	**Second survey**	**First survey**	**Second survey**	**First survey**	**Second survey**	**First survey**	**Second survey**
P1	9	161	157	22	21	2.3	2.3	0.7	0.8
P2	8	58	67	20	22	2.6	2.7	0.9	0.9
P3	8	90	103	13	14	1.9	2.0	0.7	0.8
P4	8	95	81	14	13	2.0	2.1	0.8	0.8
P5	8	109	112	15	15	2.1	2.2	0.8	0.8
P6	9	132	135	15	16	1.9	2.0	0.7	0.7
P7	8	57	57	11	11	1.5	1.6	0.6	0.7
P8	9	52	52	13	15	2.5	2.6	1.0	1.0
P9	9	202	183	16	17	1.6	1.7	0.6	0.6
P10	9	145	125	16	15	2.0	2.0	0.7	0.8
P11	9	26	25	9	9	1.7	1.6	0.8	0.7
P12	8	179	182	19	18	2.1	2.2	0.7	0.8
Mean (SD)	8.5 (0.5)	108.8 (55.7)	106.5 (51.9)	15.3 (3.7)	15.5 (3.7)	2.0 (0.3)	2.1 (0.3)	0.7 (0.1)	0.8 (0.1)

3.4.2 Mortality and recruitment rates

Demographic rates related to stem turnover for the dominant miombo species and for each plot are shown in Table 3.4.

Table 3.4 Recruitment, mortality and turnover rates for stems ≥40 cm diameter surveyed in Kilwa District, Tanzania. Results are shown for 12 plots first surveyed in 2010/2011 and subsequently surveyed in 2019. Rates are given for each sample plot, relative to the number of living stems during the first survey (Initial n in the first column). IP is the intersurvey period for each plot. Mean values across all plots and for dominant species averaged across all plots in which they were present are also shown. *Brachystegia boehmii* and *Brachystegia spiciformis* were each found growing on 11 plots, while *Julbernardia globiflora* grew on 10 plots.

			Recruited		**Died**		**Turnover**
	Initial n	**IP, years**	**n**	**% per year**	**n**	**% per year**	**% per year**
Plot							
P1	161	9	18	1.2	20	1.5	1.3
P2	58	8	11	2.2	2	0.4	1.3
P3	90	8	22	2.8	9	1.3	2.0
P4	95	8	10	1.3	22	3.2	2.2
P5	109	8	27	2.8	24	3.1	2.9
P6	132	9	34	2.6	31	2.9	2.8
P7	57	8	9	1.8	9	2.1	2.0
P8	52	9	14	2.7	14	3.4	3.1
P9	202	9	30	1.6	49	3.0	2.3
P10	145	9	19	1.4	39	3.4	2.4
P11	26	9	3	1.2	3	1.4	1.3
P12	179	8	28	1.8	24	1.8	1.8
Plot mean	**108.8**	**8.5**	**18.8**	**1.9**	**20.5**	**2.3**	**2.1**
(SD)	**(55.7)**	**(0.5)**	**(9.7)**	**(0.6)**	**(14.3)**	**(1.0)**	**(0.6)**
Species			**Plot mean for each species (SD)**				
B. boehmii	25.6	8.5	2.4	0.8	4.9	2.7	2.1
	(18.5)	(0.5)	(2.4)	(0.6)	(5.0)	(4.0)	(2.1)
B. spiciformis	23.9	8.5	3.8	2.0	3.2	1.9	2.6
	(19.5)	(0.5)	(3.8)	1.7)	(3.9)	(3.2)	(1.8)
J. globiflora	27.6	8.5	2.9	0.9	9.5	4.9	3.2
	(26.0)	(0.5)	(3.5)	(1.0)	(10.5)	(3.3)	(1.4)

3.4.3 Variables associated with stem growth and mortality

In total, 408 stems (including 73 stumps) were recorded as dead in at least one of the surveys. Of these, 123 (30.1%) were recorded as dead in the first survey, 246 (60.3%) died between surveys and 39 (9.6%) were recruited into the ≥40 cm diameter size class between the surveys, but were dead by the second survey. Mortality data was missing for 4 (1.6%) of the 246 stems which died between surveys; however, 209 (85.0%) were recorded as totally killed, 26 (10.6%) were topkilled with no signs of resprouting and seven (2.8%) were resprouting. Most stems (n=106, 43.1%) were either uprooted or totally vanished with almost the same number (n=105, 42.7%) recorded as snapped, while 31 stems (12.6%) were standing. Potential causes of mortality were noted (sometimes multiple causes for each stem, hence percentages given total >100%), including fire (n=102, 41.5%), termites (n=98, 39.8%), human causes (deduced from e.g. saw or axe marks, n= 25, 10.2%) and wind (n=38, 15.4%). For 69 stems (28.0%), the cause of death could not be identified.

The growth and mortality models were parameterised on 1009 stems and 1298 stems, respectively. Model intercepts represent the mean estimated growth rate and odds of mortality across all species and plots, relative to baseline conditions (the mean of initial stem diameter and probability of plot burn, no damage/no cambium exposure and an intersurvey period of 8 years; Table 3.5). The models estimated a mean dMAI of 3.06 mm yr^{-1} (marginal / conditional R^2 = 0.019 / 0.060) and baseline odds of mortality as 0.07 (marginal / conditional R^2 = 0.032 / 0.317) with an intersurvey period of 8 years (considered as a probability: stems, on average had 6.3% chance of mortality between surveys or 0.8% probability of dying each year assuming equal chances of mortality year on year; Figure 3.1).

Table 3.5 Predictor data included in growth and mortality models, parameterised on stems ≥40 cm diameter surveyed in Kilwa District, Tanzania. Twelve plots were first surveyed in 2010/2011 and subsequently surveyed in 2019. The growth and mortality models were parameterised on 1009 stems and 1298 stems, respectively. Baseline conditions in the model were: the mean of numeric variables (initial stem diameter and probability of plot burn), no damage/no cambium exposure and an intersurvey period of 8 years.

Parameter	Model	Summary of predictor data
Initial stem diameter	Growth	Mean across all stems: 49.7 ± 8.8 mm
	Mortality	Mean across all stems: 49.9 ± 9.1 mm
Probability of plot burn	Growth	Mean across all stems: 0.57 ± 0.23
	Mortality	Mean across all stems: 0.56 ± 0.23
Damage recorded during the first survey	Mortality	1056 (81%) stems had no initial damage recorded during the first survey
Cambium exposure recorded during the second survey	Growth	824 (82%) stems did not have cambium exposure recorded during second survey
Intersurvey period	Growth, mortality	490 (49%) and 588 (45%) stems with an intersurvey period of 8 years included in the growth and mortality models, respectively
Plot	Growth, mortality	12 plots
Species	Growth, mortality	41 and 42 species included in the growth and mortality models, respectively

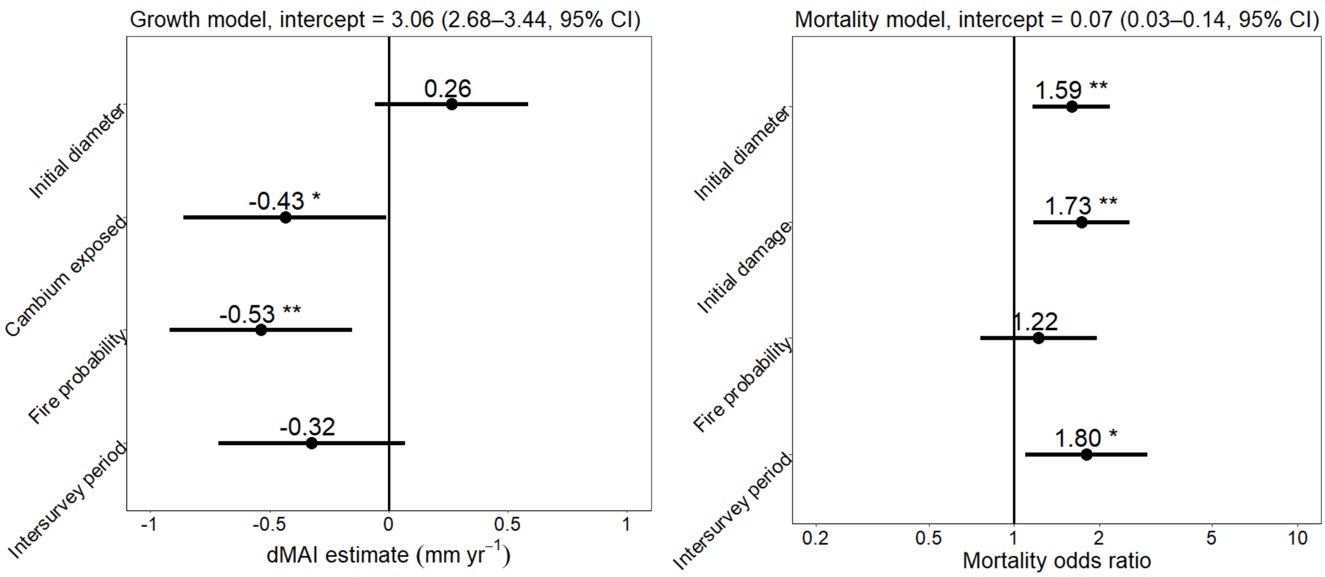
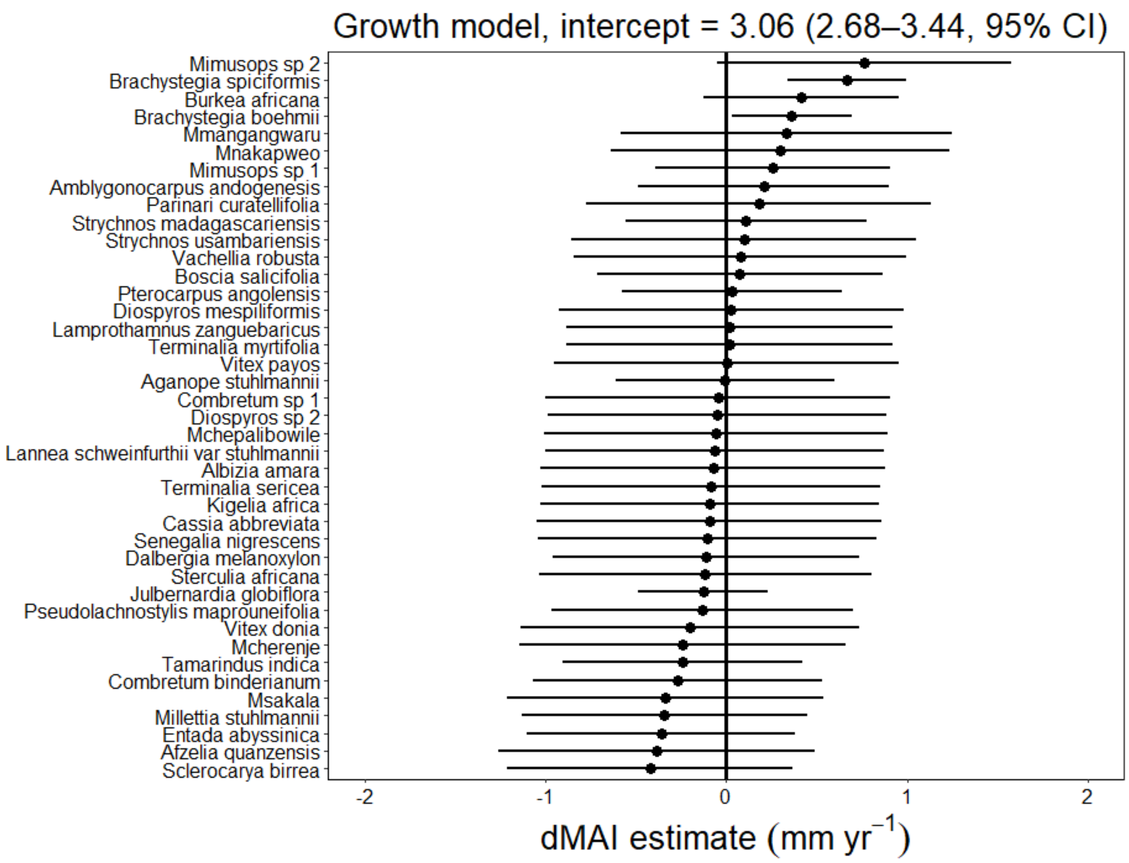


Figure 3.1 Fixed effects estimates from growth and mortality models for stems ≥40 cm diameter in Kilwa District, Tanzania, first surveyed during 2010/2011 and resurveyed during 2019. Estimates are relative to model intercepts based on reference conditions of no cambium exposure recorded during the second survey (growth model), no damage recorded during the first survey (mortality model) and an intersurvey period of 8 years. Continuous numeric parameters included in the models (initial stem diameter and number of fires) were scaled by subtracting the sample mean and dividing by two standard deviations, to aid comparisons with binary parameters (Gelman et al., 2020). Error bars indicate 95% confidence intervals; * indicates p-value <0.05, ** indicates p-value <0.01.

Both cambium exposure and increased fire probability significantly reduced growth rates to a similar magnitude, as indicated by model results from the scaled data (Figure 3.1). In real terms, on average, dMAI for a stem with an exposed cambium was reduced by 0.43 ± 0.22 mm yr^{-1} (SEM) compared to a stem with bark intact. Increasing probability of burning by 1 (i.e. annual burning) resulted in a dMAI reduction of 1.12 ± 0.43 (SEM) mm yr^{-1} (calculated by dividing the coefficient estimate in the scaled model by two standard deviations). There was a small but not statistically significant effect of stem diameter on dMAI, with the model estimating that an increase in stem diameter by 1 cm increased growth by 0.01 ± <0.01 (SEM) mm yr^{-1} on average (coefficient estimate in the scaled model divided by two standard deviations). There was also a small but not statistically significant effect of intersurvey period, whereby stems measured 9 years apart grew 0.32 ± 0.20 (SEM) mm yr^{-1} slower than stems measured 8 years apart. Species explained 3.8% and plot 0.4% of the total variance remaining in the model.

There was no clear effect of the number of fires on mortality odds ratio, but larger stems, previously damaged stems and stems measured 9 years apart were associated with higher mortality odds, with similar effect sizes as indicated by the scaled data (Figure 3.1). An increase in diameter of 1 cm was associated with an odds ratio of mortality of 1.03 (calculated by dividing the coefficient estimate in the scaled model by two standard deviations). Stems which were recorded as damaged during the first survey and stems with an intersurvey period of 9 had mortality odds ratios of 1.73 and 1.80, respectively. Species explained 27.7% and plot 1.7% of the total variance remaining in the model.

Many of the individual species effects in both models were uncertain (Figure 3.2). However, the common miombo species had more tightly constrained effects: *J. globiflora* grew slowly and had an increased odds of mortality relative to the model intercepts, while both *B.boehmii* and *B. spiciformis* grew relatively quickly with elevated odds of mortality.


Growth model, intercept = 3.06 (2.68–3.44, 95% CI)
Mimusops sp 2
Brachystegia spiciformis
Burkea africana
Brachystegia boehmii
Mmangangwaru
Mnakapweo
Mimusops sp 1
Amblygonocarpus andogenesis
Parinari curatellifolia
Strychnos madagascariensis
Strychnos usambariensis
Vachellia robusta
Boscia salicifolia
Pterocarpus angolensis
Diospyros mespiliformis
Lamprothamnus zanguebaricus
Terminalia myrtifolia
Vitex payos
Aganope stuhlmannii
Combretum sp 1
Diospyros sp 2
Mchepalibowile
Lannea schweinfurthii var stuhlmannii
Albizia amara
Terminalia sericea
Kigelia africa
Cassia abbreviata
Senegalia nigrescens
Dalbergia melanoxylon
Sterculia africana
Julbernardia globiflora
Pseudolachnostylis maprouneifolia
Vitex donia
Mcherenje
Tamarindus indica
Combretum binderianum
Msakala
Millettia stuhlmannii
Entada abyssinica
Afzelia quanzensis
Sclerocarya birrea
-2
-1
0
1
2
dMAI estimate (mm yr^{-1})

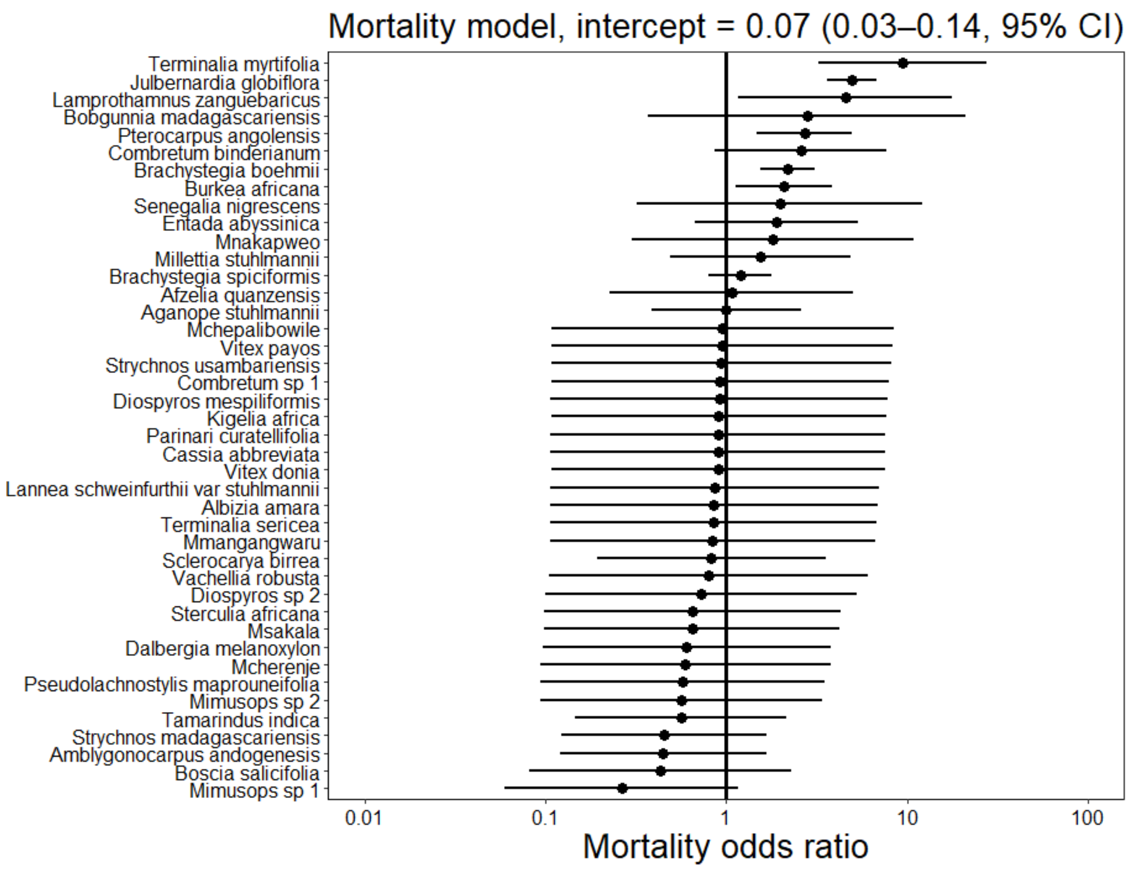

Mortality model, intercept = 0.07 (0.03–0.14, 95% CI)
Terminalia myrtifolia
Julbernardia globiflora
Lamprothamnus zanguebaricus
Bobgunnia madagascariensis
Pterocarpus angolensis
Combretum binderianum
Brachystegia boehmii
Burkea africana
Senegalia nigrescens
Entada abyssinica
Mnakapweo
Millettia stuhlmannii
Brachystegia spiciformis
Afzelia quanzensis
Aganope stuhlmannii
Mchepalibowile
Vitex payos
Strychnos usambariensis
Combretum sp 1
Diospyros mespiliformis
Kigelia africa
Parinari curatellifolia
Cassia abbreviata
Vitex donia
Lannea schweinfurthii var stuhlmannii
Albizia amara
Terminalia sericea
Mmangangwaru
Sclerocarya birrea
Vachellia robusta
Diospyros sp 2
Sterculia africana
Msakala
Dalbergia melanoxylon
Mcherenje
Pseudolachnostylis maprouneifolia
Mimusops sp 2
Tamarindus indica
Strychnos madagascariensis
Amblygonocarpus andogenesis
Boscia salicifolia
Mimusops sp 1
0.01
0.1
1
10
100
Mortality odds ratio

Figure 3.2 (above) Species estimates from growth and mortality models for stems ≥40 cm diameter in Kilwa District, Tanzania, first surveyed during 2010/2011 and resurveyed during 2019. Estimates are relative to model intercepts based on reference conditions of no cambium exposure recorded during the second survey (growth model), no damage recorded during the first survey (mortality model) and an intersurvey period of 8 years. Error bars indicate 95% confidence intervals.

3.4.4 Changes to aboveground carbon storage

On average, each 9-hectare plot stored 10.6 ± 5.0 tC ha^{-1} in its large trees during the first survey, and 10.9 ± 5.1 tC ha^{-1} in the second survey (Table 3.6); this increase was not statistically significant (t=0.74, df=11, p=0.47). The mean change in AGC was 0.03 ± 0.12 tC ha^{-1} yr^{-1} across all plots (Figure 3.3).

Table 3.6 Aboveground carbon stored in living stems ≥40 cm diameter surveyed in Kilwa District, Tanzania, first surveyed during 2010/2011 and resurveyed during 2019. The number of living stems on each 9-hectare plot and mean quantity of carbon (in tonnes) stored per hectare are shown for the first and second plot surveys.

	N living stems		**C stored per hectare**	
Plot	**First survey**	**Second survey**	**First survey**	**Second survey**
P1	161	157	17.8	18.6
P2	58	67	7.4	8.6
P3	90	103	9.0	10.8
P4	95	83	9.7	8.9
P5	109	112	13.1	11.9
P6	132	135	12.8	12.6
P7	57	57	5.3	5.7
P8	52	52	5.0	4.9
P9	202	183	16.9	16.8
P10	145	125	13.0	12.1
P11	26	25	2.1	2.3
P12	179	183	15.5	17.0
Mean (SD)	108.8 (55.7)	106.8 (51.9)	10.6 (5.0)	10.9 (5.1)

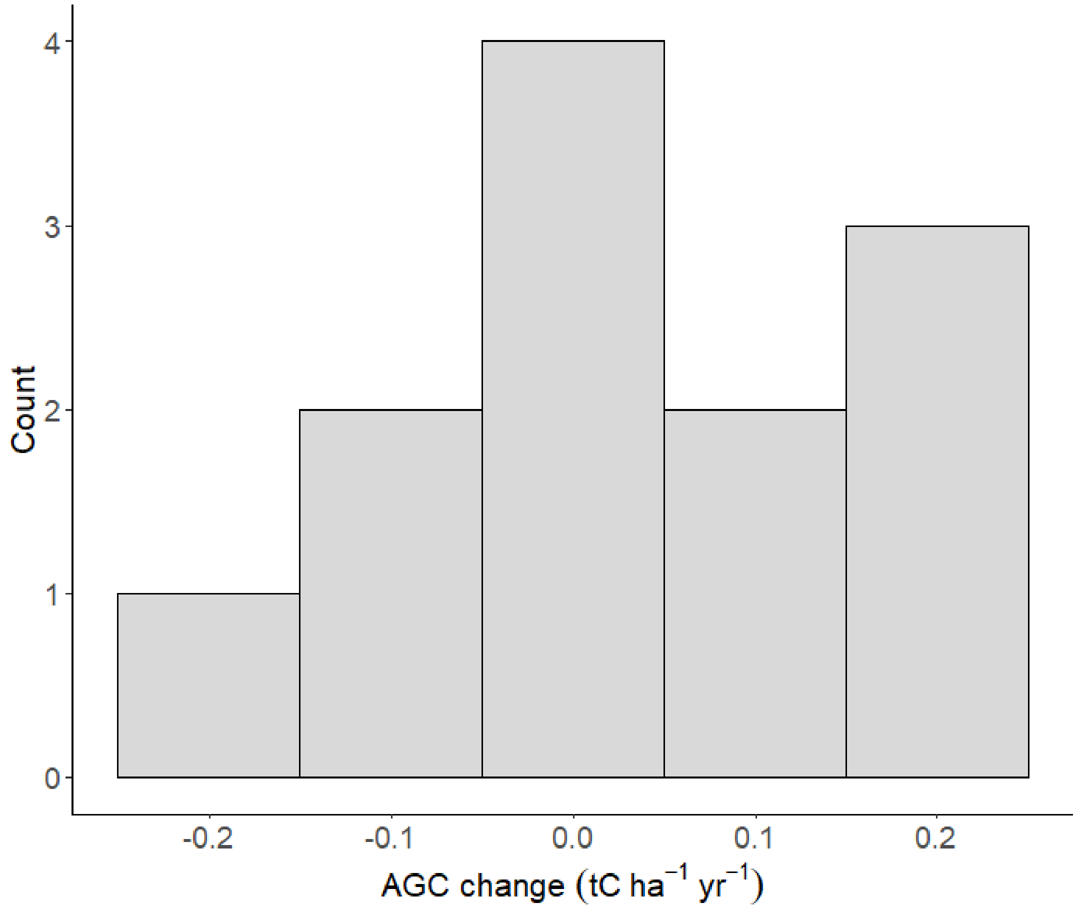


Figure 3.3 Mean annual change in aboveground carbon stored in living stems ≥40 cm diameter in Kilwa District, Tanzania, first surveyed during 2010/2011 and resurveyed during 2019, summarised for 12 survey plots.

3.4.5 Findings from focus group discussions

Most of the survey plots were on government-owned land, and there was evidence of previous commercial logging in some areas. Stems are also selected by local people for different uses based mainly on their species and condition (e.g. whether the stem is termite damaged or rotting), with size also being important for some uses. Respondents consistently reported that the primary local use of large trees is for timbers used in building homes and furniture. Particular species are chosen for qualities like their durability, resistance to termite damage, and desired size. The preferred species mentioned by respondents and their presence across all plots during woodland surveys are given in Table 3.7.

Table 3.7 Preferred species selected for timber in Kilwa District, Tanzania as noted by respondents during 12 focus group discussions. Local names and their assumed Latin names are given as well as number of living stems and stumps of each species recorded during the two woodland surveys (in 2010/11 and 2019).

Local name	Latin name	N living stems First survey	N living stems Second survey	N stumps First survey	N stumps Second survey
Mkongo	*Afzelia quanzensis*	9	11	2	2
Mninga bonde[1,2]	*Pterocarpus tinctorius*	0	0	0	0
Mninga jangwa, Mtumbati[3,4]	*Pterocarpus angolensis*	58	52	36	32
Mpanagapanga	*Millettia stuhlmannii*	17	19	7	8
Mpingo	*Dalbergia melanoxylon*	8	15	0	1
Msekeseke	*Bobgunnia madagascariensis*	1	0	2	3
Msufi pori[5]	*Rhodognaphalon mossambicense*	0	0	0	0
Mvule[6]	*Milicia excelsa*	0	0	0	0

Sources used to verify Latin names when not verified in the field:
[1] Lukumbuzya K. and Sianga C. 2017. *Overview of the Timber Trade in East and Southern Africa: National Perspectives and Regional Trade Linkages*. TRAFFIC and WWF. Cambridge, UK. TRAFFIC.
[2] Mwakajumba E. 2015. *Sustainable timber harvesting in village forest reserves in Tanzania: Lessons learned from Kilwa and Kiteto.* Tanzania Forest Conservation Group (TFCG) Technical Paper 47.
[3] International Tropical Timber Organization. 'Muninga'. Available online (accessed 10th February 2022): www.tropicaltimber.info/specie/muninga-pterocarpus-angolensis/
[4] Chudnoff M. 1984. *Tropical Timbers of the World.* United States Department of Agriculture, Forest Service. Agricultural Handbook Number 607: 265.
[5] Data from 2010/11 plot survey.
[6] World Agroforestry Center (ICRAF). *Agroforestry species profile 'Milicia excelsa'*.

Several of these species and others were said to be scarcer now compared to previous years, due to these stems being popular to harvest (though the rate of change was not clear). Species mentioned included: Mninga, Mvule, Mpingo, Mkongo, Mkarati, Msekeseke, and Mpangapanga. It was also noted that Mpingo is harvested to make handicrafts for export. Respondents said that if they couldn't find their preferred species close to the village, they would either search further afield or find an alternative species. Respondents mentioned *Adansonia digitata* (baobab or Mbuyu in Swahili) as large stems which are not cut because they are valued for the fruits and medicines they provide.

3.5 Discussion

The results reported here indicate that large tree biomass and diversity remained stable between the first woodland survey in 2010/11 and the second in 2019. Mean annual turnover across the plots was 2.1 ± 0.6%, with mortality rates marginally exceeding recruitment (2.3 ± 1.0% compared to 1.9 ± 0.6%; Table 3.4). Stem growth and recruitment offset mortality, with very little change to AGC (which, on average, increased by 0.03 ± 0.12 tC ha^{-1} yr^{-1}; Figure 3.3) or alpha diversity (Table 3.3) between the two surveys. Given that large stems store around one third of all aboveground carbon in Kilwa's woodlands (McNicol et al., 2018), the carbon stocks reported here (averaging at 10.9 ± 5.1 tC ha^{-1} in the second survey) are comparable with the average above-ground carbon stocks (33.9 ± 1.3 tC ha^{-1}) of old-growth miombo woodland reported in the review conducted by Gumbo et al. (2018). Kilwa's savannas, woodlands and forests on average store 24 ± 16 tC ha^{-1} in stems ≥5 cm diameter (McNicol et al., 2018).

This study presents a very limited account of changes to miombo diversity, excluding smaller trees, grasses and forbs, not to mention faunal diversity (Frost, 1996). However, trees – particularly the miombo dominants – play a keystone role in dictating other aspects of woodland functioning and diversity (Moura et al., 2017). Their status therefore gives at least a partial indication of the status of downstream processes, for example butterfly abundance and diversity, which have been found to be reduced in highly utilised (due to timber cutting and other types of resource extraction) miombo woodlands in southwestern Tanzania (Jew et al., 2015). Tree diversity has also been found to correlate with AGC (Shirima et al., 2015; McNicol et al., 2018; Godlee et al., 2021). The relative stability of the diversity and abundance of the large diameter trees studied here therefore provides at least some optimism that other ecosystem service provision dependent on these species may also be relatively stable.

Average growth rates across all species and plots was 3.06 ± 0.19 (SEM) mm yr^{-1} (Figure 3.1). This falls within ranges found elsewhere, though stem growth rates reported in savannas are highly variable (Swemmer & Ward, 2019). A model parameterised on data from Kilwa and the Gorongosa District of Mozambique including stems ≥5 cm diameter, estimated mean growth rates of 1.81 ± 0.17 (SEM) mm yr^{-1} (Brade, 2021). The author identified variables associated with significant reductions in growth rate including high levels of tree-tree competition, stem wounding, and increasing initial stem size. Chidumayo (2019) reported modelled growth rates in Zambian miombo of 1.0–2.4 mm yr^{-1} for 100 year old stands, and found that stand age and tree density influenced growth increment, and also reported higher growth rates in higher rainfall miombo.

Our model estimated that annual burning was associated with a dMAI reduction of 1.12 ± 0.43 (SEM) mm yr^{-1}. Fire has also been found to significantly reduce dMAI of adult stems in Australian savannas (Murphy et al., 2010) and sapling growth (measured as change in height rather than diameter) in a South African savanna (Staver et al., 2009), though the interactive effect between fire and herbivory reduced growth to a greater degree in the latter. However, fire frequency did not significantly affect growth rates in the model developed by Brade (2021) and was not included in Chidumayo (2019)'s model (though the author reported losses of biomass due to fire-induced mortality). Our model estimated that the dMAI of stems with an exposed cambium was 0.43 ± 0.22 mm yr^{-1} (SEM) lower than stems with bark intact. This finding does not represent the direct impact of bark loss at the point of measurement because, in these cases, the point of measurement was moved in the second survey and these stems were subsequently excluded from the growth analysis. Rather, this result more likely reflects a general effect of wounding on growth rates (Brade, 2021).

While typical of stem growth models, there was a large proportion of unexplained variance in our model which could potentially be explained by variables such as competition or rainfall, which have been included in the other growth models discussed here. However, the impacts of such parameters on growth rates vary depending upon the cohort of stems being studied (Chidumayo, 2019; Brade, 2021). For example in our model, in contrast with the findings of Brade (2021), larger stems were estimated to have faster growth (Figure 3.1; though this effect was not statistically significant). This effect may be related to the stem sizes included in this study, which excluded typically fast growing young trees (Bowman et al., 2013). There may also be complex interactive effects which have not been teased out in these models.

The baseline odds of stem mortality was 0.07 for undamaged stems with an intersurvey period of 8 years i.e. these stems, on average, had 6.3% probability of mortality between surveys or 0.8% probability of dying each year assuming equal chances of mortality year on year (Figure 3.1). An increase in diameter increased the odds of mortality in our model (1 cm increase was associated with mortality odds ratio of 1.03), while a mortality model parameterised on ≥5 cm stems in Kilwa found the opposite effect (Bowers, 2017). This contrasting result must again be interpreted with the stem cohort in mind: the model presented here excluded very small stems (<10 cm) which have increased vulnerability to top-kill by fire and herbivores (Ryan & Williams, 2011; Mapaure, 2013).

Initial damage (wounding during the first survey) was associated with a mortality odds ratio of 1.73 (Figure 3.2). This result is not surprising, although what perhaps makes it more surprising is that initial wounding was non-significant in candidate growth models (resulting in its exclusion from the final model). Wounding was not recorded systematically during the first survey (the ‘initial wounding’ variable was based on key words extracted from comments; see Table 3.1 for further details). One possible explanation for these findings, then, is that more visibly significant wounds which increased the odds of stem mortality tended to be recorded, while minor wounds – which may not affect stem survival over 8 or 9 years but could affect growth – tended not to be. Continued systematic recording of wounding in future surveys will help elucidate this effect.

Fire was noted as a cause of topkill in 41.5% of stems which died between surveys, however fire frequency did not affect mortality odds ratio in the model (Figure 3.2). A likely reason for this discrepancy is that it is difficult to qualitatively assess the impacts of fire on long-dead stems during a field study, and a dead stem which is found to be badly burned was not necessarily killed by fire. Qualitative identification of mortality drivers and mechanisms is in general difficult (McDowell et al., 2018), as indicated by the high proportion (28.0%) of stems for which potential causes of mortality could not be identified. Additionally, fire intensity which trees, in contrast to grasses, are highly sensitive to (Trollope et al., 2002), was not captured in our mortality model. The gap model developed by Ryan and Williams (2011) estimated that high intensity fires could reduce miombo woodland biomass via stem mortality at fire return intervals up to 50 years. Fire may also interact with other variables to influence stem mortality. For example, Yeaton (1988) reported that most of the 83 live trees that fell after a fire in a South African savanna had been previously scarred by porcupines. Elephant damage and prior frost may also increase fire-driven mortality, as reported in a Kalahari woodland in Zimbabwe (Holdo, 2005). In this study, multiple possible causes of mortality were often noted for individual stems, but it is not clear whether these effects interacted to cause stem death.

Human causes of mortality were noted in 10.2% of stems which died between surveys – usually indicated by saw or axe marks. Of the stems noted by respondents during focus group discussions as preferable to harvest for timber, living *Afzelia quanzensis*, *Pterocarpus angolensis*, *Millettia stuhlmannii* and *Dalbergia melanoxylon* stems were present in both surveys with no clear indication of increased levels of harvest (Table 3.7). Perhaps an exception to this was *P. angolensis* which reduced from 58 to 52 stems between surveys, but sample sizes were too small to draw definitive conclusions. The other species mentioned were not present at all (as stumps or living stems) in the surveys, with the exception of one *Bobgunnia madagascariensis* stem in the first survey which had died by the second.

Respondents noted that they had seen a decline in many of the noted preferred species. It is likely that the period during which this decline had been observed was much longer than the study period here i.e. the baseline for monitoring degradation established during 2010/11 in this study was shifted compared to previous decades (Soga & Gaston, 2018). Respondents subsequently had to harvest alternative species or travel further afield to find appropriate stems for timber use. Long-term declines in *P. angolensis* and concerns about the sustainability of harvest levels in Tanzania, partly due to slow growth and low recruitment rates of this species, have been reported elsewhere (Schwartz et al., 2002; Jew et al., 2016). This species is widely used for timber both domestically and for export, and it is illegal to harvest *P. angolensis* stems with a diameter of <60 cm, though smaller stems continue to be harvested (Caro et al., 2005). In this study, *P. angolensis* made up 70.6% (n=36) and 65.3% (n=32) of stumps recorded during the first and second surveys, respectively. This indicates relatively high rates of harvest of large individuals of this species historically; during the between survey period, 15 stems of this species died and 10 were recruited.

In general, it was difficult to identify species-level trends in this study due to low sample sizes, aside from some tentative conclusions regarding the dominant miombo species: *B. boehmii*, *B. spiciformis*, and *J. globiflora* (Table 3.2). Of particular interest, *J. globiflora* had a relatively high annual mortality rate of 4.9 ± 3.3% across all plots (mortality odds ratio was also higher than average in this species) compared to a low recruitment rate of 0.9 ± 1.0% and relatively slow growth (Table 3.4 & Figure 3.2). Ribeiro et al., (2013) also found high rates of mortality and low recruitment in *J. globiflora* compared to other species in a miombo woodland in Mozambique, citing pressure from harvesting and low tolerance of fires as possible causes for this. The same lead author and colleagues previously found that miombo species *J. globiflora*, *B. boehmii* and *Burkea africana* were vulnerable to damage by elephants and fires (Ribeiro et al, 2008). Chinder et al. (2020), also working in Mozambique, reported that *J. globiflora* resprout growth rates following fire were reduced in frequently burned areas with a fire return interval of 2 years compared with 3.6 years. This species may therefore be sensitive to current levels of disturbance in Kilwa, but this finding is far from clear.

3.6 Conclusions

In this study I provide evidence that current rates of disturbance in a miombo woodland in south-eastern Tanzania are congruent with stable biomass and diversity of large-diameter stems, with mean annual AGC gains of 0.03 ± 0.12 tC ha^{-1} yr^{-1}. Mean annual turnover across the plots was 2.1 ± 0.6%, with stem growth and recruitment offsetting mortality. Results from modelling and focus group discussions suggest that wounding, harvesting, and fire may represent constraints on individual growth and/or survival of large diameter stems. The data and models presented here can provide only comparisons between stem estimates, rather than determining causality (Gelman et al., 2020) and so must be treated with caution. Yet these results point to potential drivers of degradation, and how they are currently impacting large trees. I found that stem wounding increases mortality and reduces growth while fire reduces growth but does not increase mortality rates in large stems. This contrasts with assumptions that large stems are unaffected by fires, but shows that large stems are resilient to the current fire regime. I recommend that systematic recording of stem wounding should be included in woodland surveys in order to determine impacts on growth and mortality rates, including when interacting with fire. Higher resolution data on fire frequency (Ramo et al., 2021) would help further refine understanding of the effects of fire on demographic rates and inform sustainable management.

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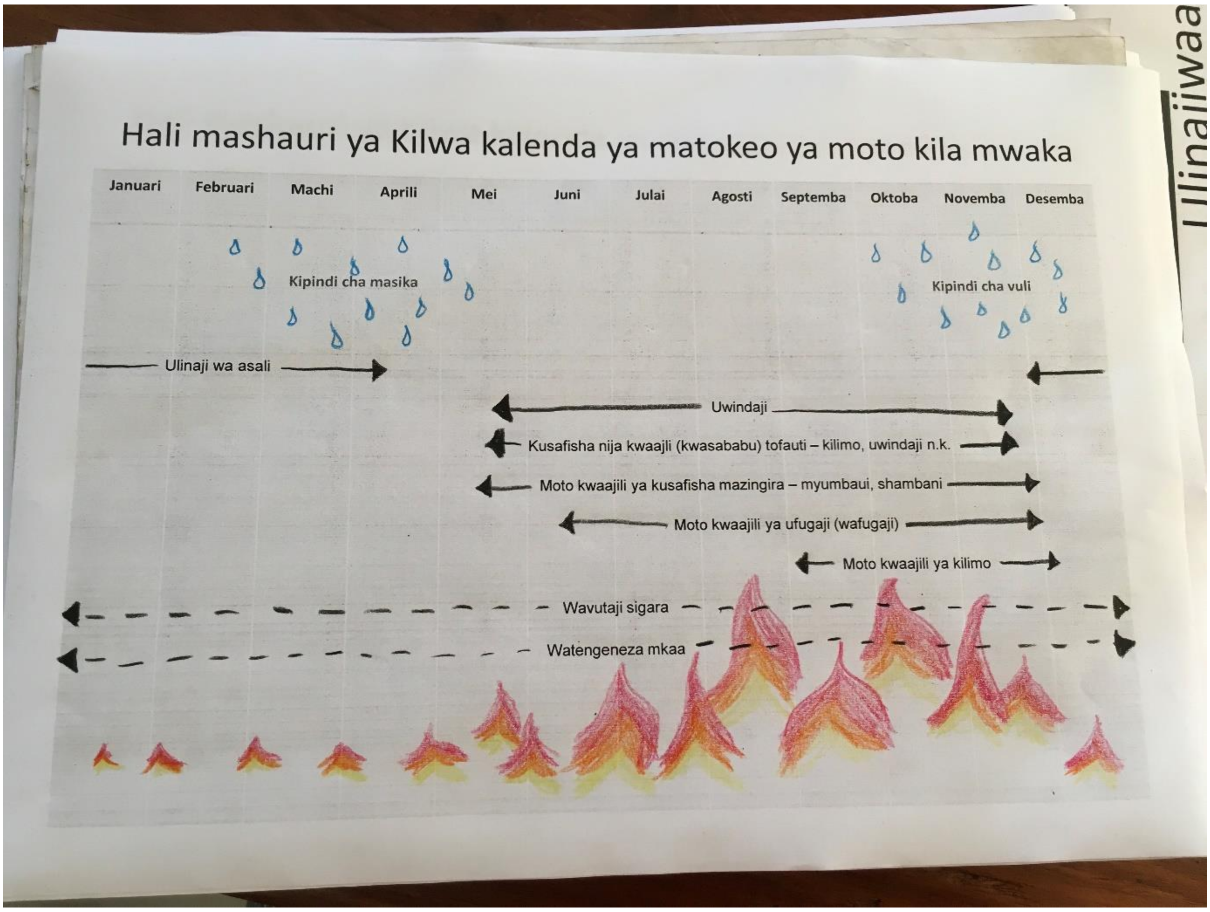
Chapter 4. Intentions behind common and risky fires in south-eastern Tanzania



Fire calendar presented to villages during focus group discussions in Kilwa District, Tanzania (Ellie Wood, 2019).

Chapter 4. Intentions behind common and risky fires in south-eastern Tanzania

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Author contributions: EW designed the data collection, with inputs from CMR, KS, JAF and IG. EW and MM collected the social data; EW led the thematic analysis with inputs from MM and KS. CA led the remote sensing analysis with inputs from EW and CMR. EW led the writing of the manuscript; all other authors reviewed the manuscript and suggested improvements.

4.1 Abstract

Human-set fires are a crucial component of African savannas, affecting ecosystem structure, carbon emissions, local hazards and livelihoods. Yet, most fire research in these ecosystems focuses on the fire ecology of protected areas. Research exploring fire regimes in inhabited landscapes remains limited, undermining opportunities for culturally and environmentally sustainable fire management. To address this gap, we used interviews in Tanzanian farming communities and remote sensing to identify intentions behind fire use and the perceived relative frequency and riskiness of fires set for different purposes. We found that the most common ignitions were intentional and important to livelihoods. Burning was adaptive, responsive to environmental conditions, and optimised for the intended outcome with the perceived riskiest fires intentionally spreading uncontrolled. Remote sensing showed that most of the total burned area was accounted for by fires during the late dry season when people burned for activities, such as field preparation, and when environmental conditions encouraged fire spread. Our findings offer an insight into fire regimes in inhabited landscapes, by exploring how intentions shape the fire regime at the landscape scale. We discuss how understanding these intentions and local priorities, including adaptive uses of fire, is key to sustainable fire management outside protected areas.

4.2 Introduction

Fire regimes in African savannas and woodlands are made up of individual fires that vary in extent, intensity (temperature), frequency, timing and location (Bowman et al., 2011). Observational and experimental evidence shows that variations in these aspects of fire regimes dictate fire severity and associated impacts on vegetation, litter and soils (Trapnell 1959; Lawton 1978; Kikula 1986; Whelan 1995; Staver et al., 2011). For example, less intense and less frequent fires allow greater tree recruitment and cover (Ryan and Williams 2011). This affects the suite of services provided by ecosystems (arguably, in both positive and negative ways), such as carbon storage, biodiversity and the myriad ways savannas support local livelihoods (Ryan et al., 2016).

Humans modify fire regimes across African savannas with impacts on greenhouse gas emissions and ecosystem dynamics (Archibald 2016; Ramo et al., 2021). Many of these modifications are indirect, as both local land use and global climate change alter wind speed, fuel load, continuity, and moisture (Bowman et al., 2011). In particular, land use change has decreased landscape connectivity over time, causing total burned area and associated emissions to decrease in many human-dominated parts of the world, including the most populated parts of Africa (Archibald 2016; Andela et al., 2017). People also directly impact fire regimes by setting and suppressing fires and, outside protected areas, human ignition patterns have strong influences on fire regimes (Archibald et al., 2010). Fire is commonly used to support livelihood activities in rural communities, such as to prepare agricultural fields, to promote fresh grazing for livestock, deter pests and create firebreaks (e.g. Kull 2004; Eriksen 2007; Shaffer 2010).

Considerable research over several decades has explored the biophysical aspects of fire management in national parks and conservation areas of different African ecosystems (e.g. Bond and Archibald 2003; Govender et al., 2006; van Wilgen et al., 2007; Ribeiro et al., 2019a). This has informed fire management in protected areas, particularly the use of prescribed burning early in the dry season to reduce fire spread and intensity later in the dry season, which may enhance biodiversity (e.g. van Wilgen et al., 2008, but see also Parr and Andersen 2006). In inhabited African landscapes, studies incorporating local knowledge have found that fire management is influenced by multiple social and cultural dynamics, including historic fire policies (often fire suppression), conservation goals and current fire management best practices (often prescribed burning, based on biophysical studies), local livelihoods (often dependent on burning) and social power dynamics (e.g. Eriksen 2007; Butz 2009 Shaffer 2010; Humphrey et al., 2021; Johansson et al., 2021). Research by Laris explored how human burning practices drive spatial and temporal aspects of the fire regime in southern Mali (2002), finding that traditional burning created a landscape-level seasonal mosaic with patches of unburned, early burned, and late-burned vegetation. Laris (2013) also found, using interview and remote sensing data, that human burning practices, vegetation cover type and landscape pattern are the primary drivers of the fire regime in this region. Similar landscape-level mixed methods approaches have not been attempted in southern Africa, limiting understanding of human controls over fire regimes here.

Fire management must be resilient to changing needs under shifting environmental and social conditions (McWethy et al., 2019). For example, climate change and associated changes in rainfall, expansion of cropland and urban areas are projected to be important drivers of change in African savannas in future (Dziba et al., 2020). Community-based fire management is now widely promoted as an approach for environmentally and culturally sustainable fire management, but its roll-out and success has been limited, for example in Tanzania (Kagosi et al., 2020; Kilawe et al., 2021) and Botswana (Dube 2013). Gaining better understanding of local fire use, who initiates burning, how and why people burn, can inform culturally and environmentally sustainable management and policies (Meyers 2006), especially when combined with studies exploring the ecological impacts of fire uses (Colombaroli et al., 2019).

Here, we present a case study of the fire regime in Kilwa, a rural district of south-eastern Tanzania. We report findings from interviews in rural communities to understand the role fire plays in local livelihoods. We then combine these data with remote sensing to explore linkages between fire intentions and the resulting fire regime. We asked the following questions:

1. What are the main causes of fire (human or otherwise) in Kilwa?
2. What are the human intentions and livelihoods associated with fire use?
3. How do the intentions behind fire use influence fire regimes?

4.3 Materials and methods

4.3.1 Study site and overview of methods

The study site was Kilwa District, in the Lindi Region of south-eastern Tanzania (sections 1.6 & 2.2). Satellite data were used to determine fire trends across the district, and interview data were collected from six study villages (Figure 2.1).

4.3.2 Remote sensing

The MODIS Burned Area data product (MCD64A1) was used to identify the dates and extent of burns throughout Kilwa District between 2001 and 2019. This product combines changes detected in 500 m Moderate Resolution Imaging Spectrometer (MODIS) Surface Reflectance imagery with 1 km MODIS active fire observations. The date of burns are identified for 500 m grid cells in each individual MODIS tile as the day of year on which a burn occurred (Giglio et al., 2015, 2018). The MCD64A1 data were processed in R (R Core Team 2020) to identify the total burned area for bimonthly periods within Kilwa District between 2001 and 2019, as well as to calculate crude fire return intervals; ± indicates standard errors of the mean unless otherwise noted. Figures were produced using R Version 4.0.1 (R Core Team 2020) and the ggplot2 package (Wickham 2016), and QGIS Version 3.10.10 (QGIS Development Team 2019).

4.3.3 Interviews and focus group discussions

Data were collected over a total period of six months in 2018 and 2019. A village meeting was conducted upon arrival in each of the six villages. Subsequently, data collection involved the activities detailed below.

Between September and November 2018, two focus group discussions were conducted in each village, one with men and one with women, involving between eight and 13 respondents and lasting between two and three hours. Respondents drew village maps that included where fires had occurred in the past 12 months, while discussing causes and impacts of those fires (see example in Appendix 1). Additionally, one focus group discussion with five respondents (both men and women) was conducted in each village involved in prescribed burning around the community forests. Respondents discussed the process and impacts of prescribed burning. No members of the Sukuma tribe were part of the focus group discussions because typically members of this tribe are less integrated in village affairs, and there are some difficult relations between Sukuma people and others in the village. Focus group discussions lasted between one and two hours.

Also during the 2018 field season, some 112 semi-structured interviews (between 16 and 20 in each village) were conducted with individuals and small groups, lasting between 30 minutes and two hours. Interviewees were selected based on characteristics of interest (purposive sampling), in order to build a comprehensive understanding of the fire regime. Interviewee selection was informed by learnings from village meetings, focus group discussions and other interviews, in order to explore research questions that remained unanswered or unverified. Both men and women involved in livelihood activities that use fire (e.g. farmers, hunters, charcoal makers) and those involved in activities vulnerable to fire (e.g. grass collectors) were interviewed.

Those involved in the Village and Natural Resources Committees (indicating involvement in village planning, and more interactions with local environmental NGOs), and those with no involvement in committees were interviewed. In total, five interviews were conducted with members of the Sukuma tribe. Four of the interviews in each village (two with men and two with women) were conducted as walking interviews to explore locations where there had been recent fire. General uses of fire in the village were discussed with all respondents, as well as respondent livelihood activities, their own use of fire and experiences of fire, including uncontrolled fire, and fire impacts on different types of ecosystem service (MA, 2003). Interview topics were flexible, dependent on the areas in which respondents showed particular expertise and interest.

During a second field season between September and November 2019, focus group discussions lasting between two and three hours were conducted with two groups of 10 men and women in each village (one group of members from village committees and one with non-committee members) to validate major findings and conduct ranking exercises. Potential causes of uncontrolled fire (intentionally or otherwise) common across all villages that had been identified during the previous field season were verified by each group. These causes were ranked by groups to establish the extent to which ignition sources differ in perceived frequency and riskiness of fires, while discussing reasons for the rankings.

During initial village meetings and informal discussions, and throughout the study periods, trust was built with respondents and the research aims and affiliations were clearly explained. The 'outsider' status of the researchers was minimised by travelling by public transport and eating and socialising with villagers. Although several uses of fire were subsequently discussed readily as a result, many respondents were reluctant to discuss fires that are intended to spread uncontrolled, particularly those used in hunting and livestock keeping. The likely reasons for this were discussed with some respondents who suggested this was due to fear of recrimination from neighbours or from the researchers who may be thought to represent the district authority. Therefore, multiple sources of information, gathering both individual perspectives and group consensus, were used to triangulate (validate) results (Nightingale 2020). Informal discussions and observations were also used to verify information and prompt new queries. Data were collected until the point at which new insights related to the research questions stopped emerging (i.e. theoretical saturation was reached) (Charmaz 2006; Bryman 2012).

NVivo 12 (QSR International 2018) was used to thematically analyse interview notes. Figures were produced using R Version 4.0.1 (R Core Team 2020) and the ggplot2 package (Wickham 2016).

4.4 Results

4.4.1 Overview of spatial and temporal patterns of recent fires

Remote sensing analysis found that between 2001 and 2019, on average 4890 ± 158 km^2 of Kilwa District burned annually, equivalent to 33 ± 1% the land area. On average, 99% of the total burned area was burnt between May and November, though fire seasonality varied from year to year (Figure 4.1). This was corroborated by findings from focus group discussions and interviews as respondents reported that the fire season typically shifts from year to year, depending on the timing of the rainy season. Grasses begin to burn when they are dry enough, following the end of one rainy season and before the start of the next. Respondents noted that there has been no consistent trend of the fire regime starting earlier or later over time, but that it varies between years.

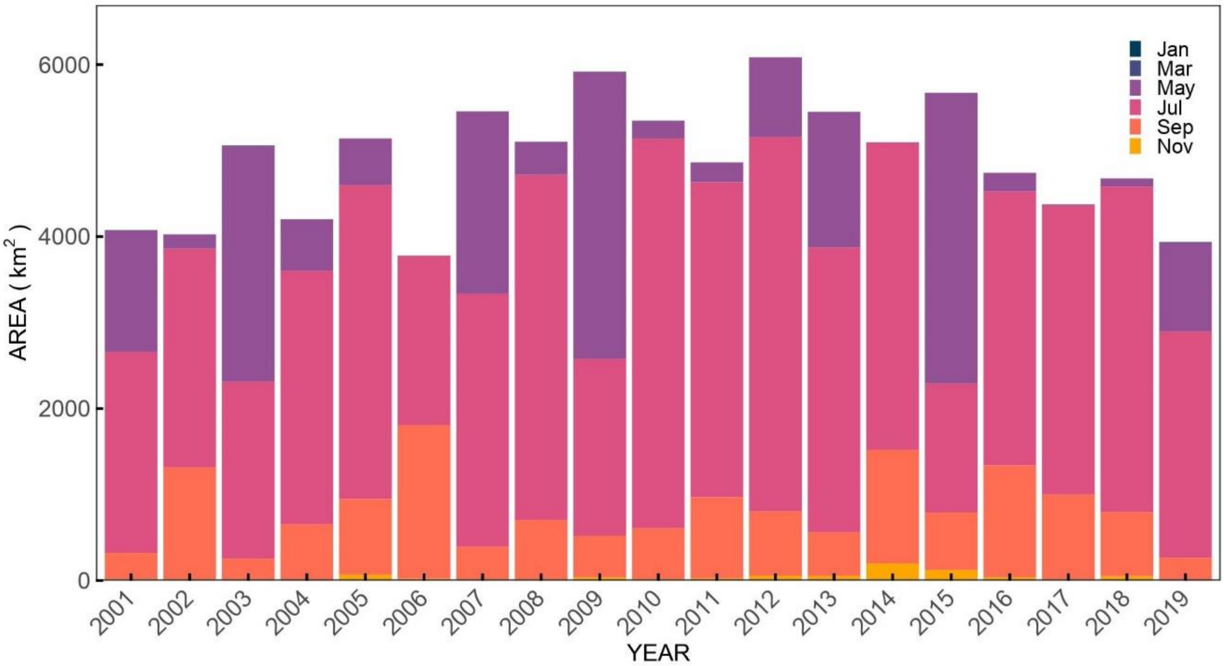


Figure 4.1 Burned area in Kilwa District, Tanzania, between 2001 and 2019. Bars show total area burned identified from the MCD64A1 Burned Area data product (Giglio et al., 2015, 2018) and processed in R (R Core Team, 2020) for bi-monthly periods. With calendar days numbered from 1 to 365/6, the time periods for non-leap years are January 1st until March 2nd (Jan), March 3rd until May 2nd (Mar), May 3rd until July 2nd (May), July 3rd until September 1st (Jul), September 2nd until November 1st (Sep), November 2nd until December 31st (Nov).

On average, 63% of the total burned area was burnt in the months of July and August alone. Respondents reported that early July is typically the start of the late dry season, when grasses have fully dried and more intense fires burn. Respondents reported that uncontrolled fires are most common during the late dry season. Each year, a larger area burned in the western part of the district, compared with the eastern (including the study villages). There was also typically a gradient of seasonality each year, with earlier fires in the western compared with the eastern part of the district. The spatial patterns of burned area for 2018 and 2019 (the years of interviews and focus group discussions for this study) are shown in Figure 4.2. Almost half of Kilwa's land area had a mean crude fire return interval of five years or less during 2001–2019 (Table 4.1). The fire return interval was 5.6 years on average, across the district, whereas 30% of the land did not burn at all during the 19-year period studied.

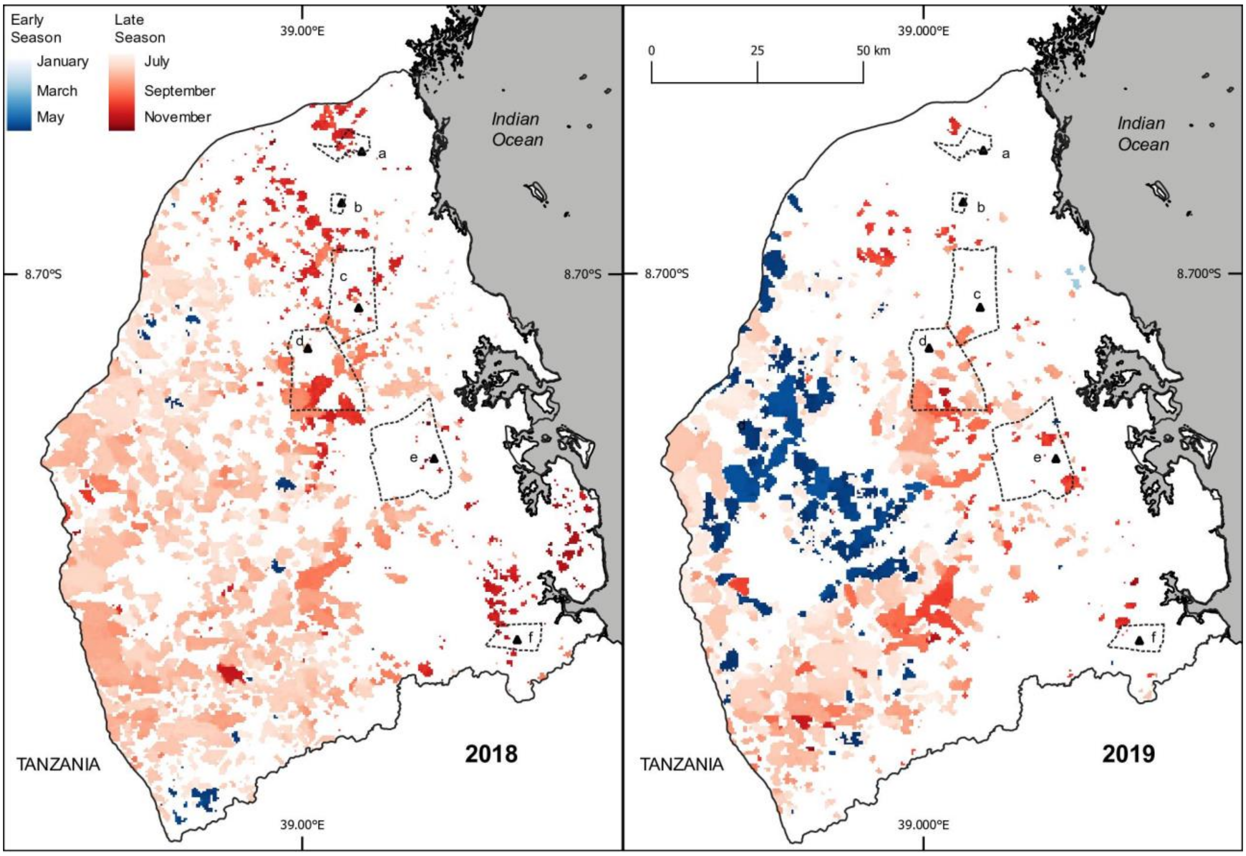


Figure 4.2 Burned area in Kilwa District, Tanzania, in 2018 and 2019 as identified from the MCD64A1 Burned Area data product (Giglio et al., 2015, 2018) and processed in R (R Core Team, 2020). The village centre (triangles) and boundaries (dotted lines) are shown for a) Mtyalambuko, b) Ngorongoro, c) Kikole, d) Ngea, e) Mchakama, and f) Mtandi. Fires between January and the end of June are shown in blue, fires between July and the end of December are shown in red.

Table 4.1 Crude mean fire return intervals between 2001 and 2019 in Kilwa District, Tanzania. The total area of land (in km^2) with a mean fire return interval falling within the ranges given (1–5 years, 6–10 years etc.) is shown. Land area as a percentage of the total land area of Kilwa District is also shown; ± indicates standard error of the mean. Burnt pixels were identified from the MCD64A1 Burned Area data product (Giglio et al., 2015, 2018) Data were processed in R (R Core Team, 2020).

Mean fire return interval (years)	Area (km^2)	Area (%)
1–5	7295.5 ± 61.8	48.6 ± 0.4
6–10	1746.9 ± 114.7	11.6 ± 0.8
11–15	0	0
16–19	1487.5	9.9

4.4.2 Potential causes of uncontrolled fires

Ten potential causes of uncontrolled fires (i.e. fires that could spread into the landscape and impact the fire regime), common across all villages, were identified during interviews and focus group discussions in 2018, and verified by focus group discussions in 2019 (Table 4.2). Most ignitions were intended to achieve specific goals and meet livelihood needs, and fire was considered important to meeting those needs:

> "Everyone uses fire… If you are going to talk about uses of fire... one quarter of human life depends on it." (Respondent at Mchakama Village Meeting 2018).

Decisions to burn for those needs tended to be made by individuals and small groups. Other causes of fire unrelated to livelihood needs included fire caused by lightning, general carelessness or actions considered reckless (often attributed to the inebriated, those who carelessly drop cigarettes, or young children playing with matches) and fire used to intentionally harm others (arson). Although fire to harm others was said to be very rare, we were told stories of people intentionally burning somebody else's crops or even home out of rage or jealously, and all focus groups stated that these fires could spread uncontrolled.

Several activities involving fire were carried out mainly by men (Table 4.2). In the study villages, only the Sukuma people used fire to generate fresh grass growth to feed their livestock (as reported by Sukuma livestock keepers and others). One Sukuma livestock owner reported a traditional method of burning firebreaks around patches of grasses that are favoured by livestock, to prevent those grasses from being burned during the dry season. This is a similar method to burning to clear a firebreak around homes and fields used by the majority of people in the study villages (Table 4.2).

Table 4.2 Fire causes and ignition conditions in Kilwa District, Tanzania.

Activity related to burning	Ignition description	Ignited by	Intended control	Habitat	Month	Time of day
Human ignition:						
Field preparation	Burning piles of cleared plant residue, or burning entire field	Men and women, individuals or small household groups and sometimes neighbours	Controlled, but fire can escape intended boundaries	Woodland, fallow, village centre	August until November (dry season)	Middle of the day to burn the entire field, evening or morning for burning piles
Clearing around homes and farms (to prevent later fires reaching these areas)	Burning piles of cleared plant residue and debris, or burning flammable vegetation directly	Men and women, individuals or small household groups	Controlled, but fire can escape intended boundaries	Woodland, fallow, village centre	May until November (dry season)	Evening or morning
Charcoal production	Burning logs in earth kiln	Usually male farmers, as an additional livelihood activity	Controlled, but fire can escape kiln	Woodland	Any month	Any time
Honey collection (to tranquilize bees)	Lighting a smoking branch	Usually male farmers, as an additional livelihood activity	Controlled, but smoking branch may be dropped after use and cause fire to spread uncontrolled	Woodland, village centre	December until April (rainy season)	Evening

Clearing a path (for ease of access and security from wild animals)	Burning grassy areas	Anyone	Spread uncontrolled	Woodland	June until November (dry season), commonly October when traveling to farms outside of village centre	Middle of the day
Hunting (to improve visibility and encourage grass growth)	Burning grassy areas	Usually male farmers, as an additional livelihood activity	Spread uncontrolled	Woodland	June until November (dry season), often later in the dry season	Middle of the day
Livestock keeping (Burning off old grasses to encourage fresh growth)	Burning grassy areas	Pastoralists, usually young men and boys are responsible for burning	Spread uncontrolled	Woodland, often areas close to rivers and other water sources that enable grass regrowth	May until November (dry season), often early or late in the dry season, when recent or upcoming rains enable grass regrowth	Middle of the day
Harm others	Burning someone's farm or home	Anyone	Spread uncontrolled	Homes and fields in village centre, woodland	Any month	Any time
Carelessness	Dropping a cigarette or match accidentally	Anyone	None	Anywhere	Any month	Any time

Natural ignition:

Lightning	Lightning striking flammable vegetation	NA	NA	Anywhere	January until April (rainy season)	Any time

4.4.3 Methods to optimise burning

Respondents reported that, depending on the desired outcome, fires were either intended to burn within specific boundaries or to spread uncontrolled (Table 4.2). Outcomes were achieved by choosing optimal ignition conditions, and using specific methods to set and control fires. Larger fires intended to spread uncontrolled were set in hot, dry and windy conditions, with grasses being the best fire fuel, and strong winds able to carry fires great distances and across potential firebreaks like paths. Fires intended to remain small were set in cool, still conditions, often in the morning when grasses were still wet with dew and likely to burn less intensely.

Other criteria specific to the livelihood activity also dictated the location and conditions of intentional burns. For example, some respondents reported that livelihood activities additional to agriculture, like charcoal production, were more commonly conducted during the dry season when farming is less labour-intensive. This also made activities carried out at this time of year (as well as fires caused by lightning and carelessness) more likely to cause uncontrollable fires, for example if fire escaped charcoal kilns. Conversely, honey was collected soon after flowers had bloomed in the rainy season when grasses were wet and more likely to suppress uncontrolled fire that could result from a dropped smoking branch (Table 4.2).

If the conditions were risky, but the aim was to avoid the uncontrolled spread of fire, preparations were made like burning or digging a border around a field, or choosing bare, sandy earth on which to make charcoal. Smaller fires were sometimes monitored until they burned out, and some were extinguished or controlled using green branches (*mafukutu*) and sandy soils. Farmers often told neighbours when they were going to burn their fields, so that they could control the area burned together.

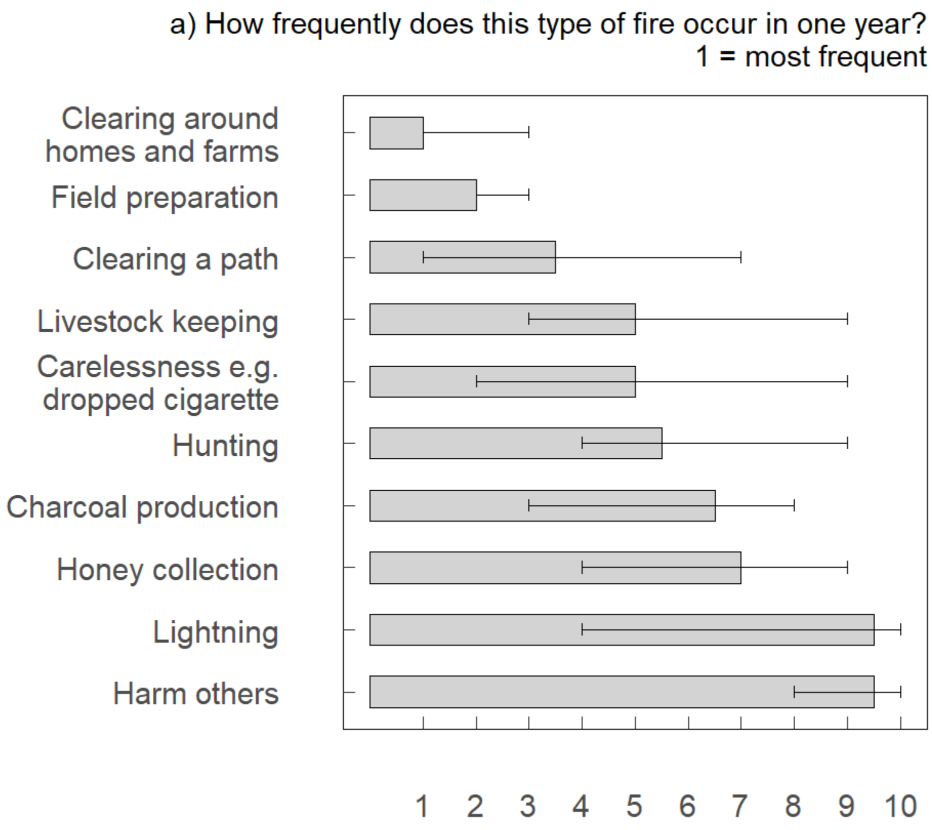
Respondents reported that most of the techniques they used to burn had been taught by their parents and grandparents, or simply that they had always burned this way. Burning agricultural debris in piles rather than burning the whole field was seen as a way to prevent damaging impacts of fire on soils, and this had been taught by government employees, known as *Bwana Shamba* or *Bibi Shamba* (terms used for men and women, respectively), who live in the villages to educate and assist local farmers. Some respondents who had been involved in prescribed burning (*ubabuaji* in Swahili) in Kikole, Mchakama or Ngea reported that involvement in community forestry and prescribed burning may have encouraged the use of similar methods elsewhere (e.g. to clean around homes and fields). However, all stated that methods like these were not new. Several respondents did not know the term *ubabuaji*, and there were a variety of other local names for methods of this type of traditional protective burning:

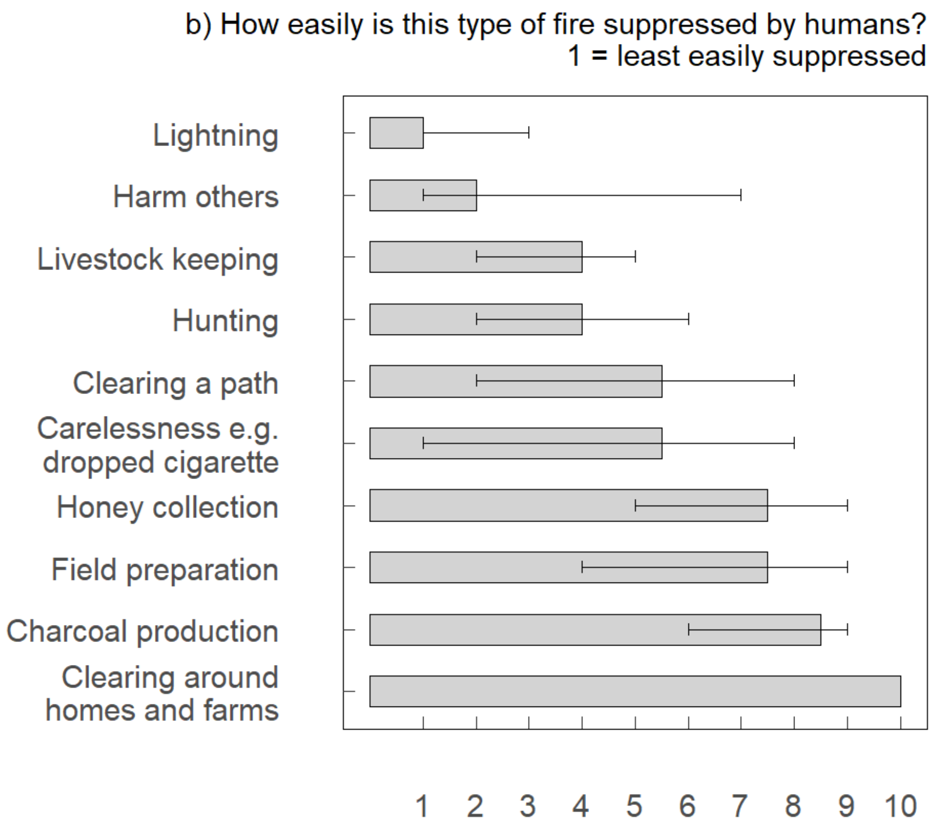
> "You start by cutting down grasses at night and then you burn where you cut down grasses, and because they are wet grasses the fire won't go far away… We call it *ubabaya*, and we have known it since our grandfathers." (Farmer; former blacksmith and hunter in Mtyalambuko 2018).

Most respondents across the villages stated that the methods of burning had not changed in their lifetimes.

4.4.4 Common and risky fires

The extent to which ignition sources differ in perceived frequency and riskiness of the resultant fire was explored during ranking exercises in 2019 (Figure 4.3). In all villages, fires to clear unwanted vegetation and burn piles of plant residue and debris around homes were reported as common; these fires were used frequently by every household. They were also considered low risk, because of their small size, because they could be easily controlled (and the incentives to do so, to protect the fire user's property, were strong), and occurred in the village centre where there is a low density of flammable grasses.


a) How frequently does this type of fire occur in one year?
1 = most frequent
Clearing around homes and farms
Field preparation
Clearing a path
Livestock keeping
Carelessness e.g. dropped cigarette
Hunting
Charcoal production
Honey collection
Lightning
Harm others
1 2 3 4 5 6 7 8 9 10


b) How easily is this type of fire suppressed by humans?
1 = least easily suppressed
Lightning
Harm others
Livestock keeping
Hunting
Clearing a path
Carelessness e.g. dropped cigarette
Honey collection
Field preparation
Charcoal production
Clearing around homes and farms
1 2 3 4 5 6 7 8 9 10

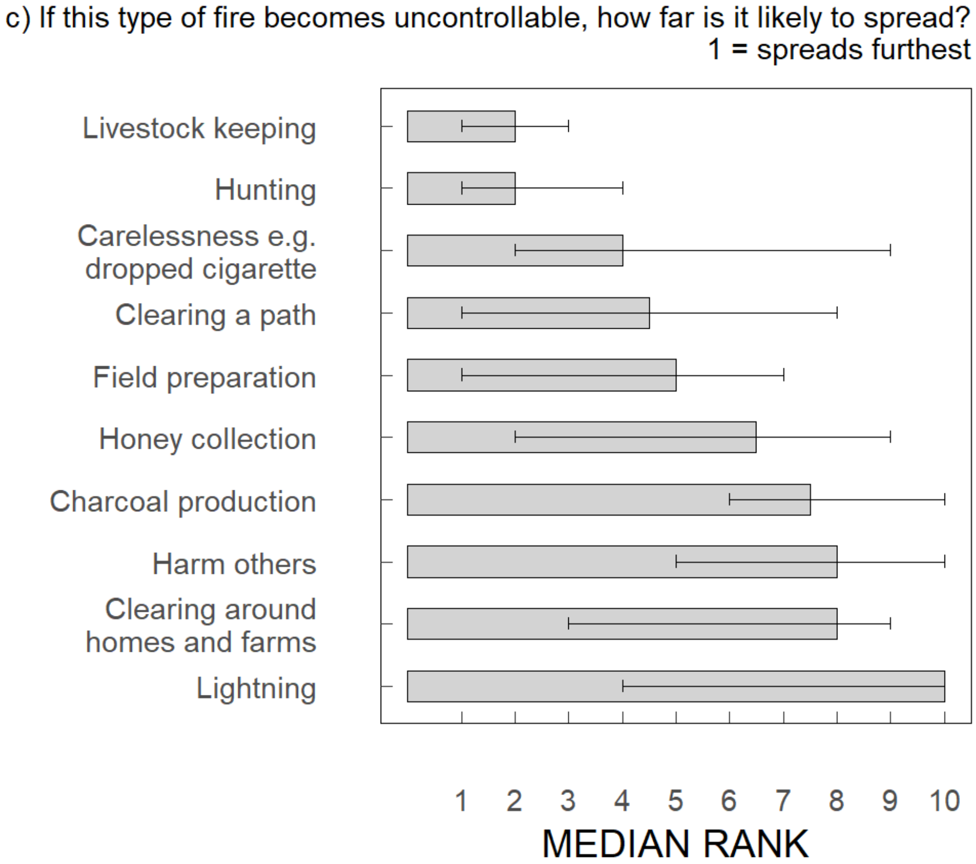


Figure 4.3 (includes previous page) Results from ranking exercises in 12 focus groups in six villages (two groups in each village) in Kilwa District, Tanzania. Ten fire causes were ranked three times by each group, answering the questions: a) how frequently does this type of fire occur in one year? b) How easily is this type of fire suppressed by humans? c) If this type of fire becomes uncontrollable, how far is it likely to spread? Median ranks across groups are shown. Error bars show the range of ranks reported across the 12 groups.

Other fire types were less consistently ranked, likely due to both genuine variation in observed fire between villages and limitations with the ranking exercise. For example, lightning fires were ranked among the three least common fire types in all villages, with most commenting that they only occurred during the rainy season, apart from in Ngorongoro, where the two groups ranked lightning as the fourth and sixth most common cause of fire. It is unclear whether this was because there had been more lightning strikes here or if people were simply more aware of it. In this village, many coconut trees are grown and lightning striking the top of coconut trees is a highly visible and reportedly common occurrence.

Respondents in ranking exercises noted that the intentions of those setting the fire partly determined its perceived riskiness. The two types of fire that spread furthest were those for hunting and livestock keeping (ranked first or second highest by 10 out of 12 and 9 out of 12 focus groups, respectively). Both of these types of fires were intended to spread uncontrolled over large areas. For other fires, the incentives to keep the fire controlled were often strong:

> "A charcoal maker wants a benefit, not a loss, so most of the time he'll be checking that the fire hasn't gone uncontrolled and his charcoal hasn't been burned. He wants some money to solve his problems, so he is careful and if the fire goes uncontrolled, it's an accident." (Respondent during ranking exercises for non-committee members in Ngea 2019).

Respondents said that fires caused by carelessness, for clearing a path, hunting or livestock keeping, to harm others and by lightning could not be controlled easily by directly preventing or extinguishing fires, but discussed how the time and place of ignition could result in indirect controls (Table 4.2):

> "Most of the time lightning happens in the rainy season when the area is still wet and grasses are still wet, so it can't spread far" (Respondent during ranking exercises for non-committee members in Ngea 2019).

However, respondents also noted that intentions did not always match up to the reality of burning and that some people had been careless by allowing controlled fires to become uncontrolled, or simply that some fires can become uncontrollable and that this was unavoidable under certain conditions.

The major causes of uncontrolled fire cited by respondents in interviews varied and included hunting, field preparation, clearing a path, or unknown reasons; those who were deemed careless or irresponsible were also often said to be the cause. Part of the uncertainty over the biggest cause of uncontrolled fires arose because of difficulty in identifying the cause of individual fires.

4.4.5 Perceived biogeophysical impacts of uncontrolled fires

Respondents reported that uncontrolled fires typically destroy herbaceous vegetation, tree seedlings and saplings, but that large trees have not been harmed by most fires. Fires were not reported to burn into the tree canopy. Many, but not all respondents, reported that uncontrolled fires could cause long-term environmental changes in areas that had been repeatedly burned, by killing trees and turning previously wooded areas to grassland, reducing soil fertility and causing water sources to dry up.

Most of the immediate impacts of uncontrolled fire had been directly observed. However, the perceived long-term effects were typically reported as having been taught by school teachers, NGOs, *Bwana Shamba* or *Bibi Shamba* (government employees assisting farmers, who taught that repeated fire can reduce soil fertility), or as being simply well-known in general. Respondents rarely reported having observed long-term effects of uncontrolled fire in their lifetimes; conversely, uncontrolled fire was reported to have always been a normal part of life, and burnt areas were observed to recover and regrow. Some areas were reported to burn annually: after the start of the rainy season, grasses regrew and the area could burn again the following year.

The benefits of burning for specific livelihood activities (Table 4.2) were seen by respondents as accruing only to the fire users, whereas the broader environmental impacts of uncontrolled fire as described above were generally seen as harmful:

> "Anything that has good impacts also has bad impacts. For example, you set fire in your field to cultivate, to get crops to sell. But (to do this) you have cut down trees and burn the area, so the land will turn to desert." (Farmer and charcoal maker in Kikole 2018).

Respondents also noted that fire hazards, when an uncontrolled fire had become dangerous or destroyed someone's property, had affected others in the community. Some who gather resources, such as thatching grasses and palms used to make mats, had lost income when they found these resources were burned. MCDI staff and community members involved in community forest management reported that it was important that the community forests, and their valuable timber species, should be protected from fire and that prescribed burning could help achieve this (though not all respondents in Kikole, Mchakama or Ngea had been involved in community forest management or prescribed burning). Therefore there was an unresolved tension between believing that uncontrolled fire has long been a normal and acceptable feature of the environment, and that it causes environmental and social harms.

4.4.6 Potential shifts in the fire regime over time

Some respondents noted social and demographic changes that had the potential to influence the fire regime in recent years, however, this was reported inconsistently. Some reported that uncontrolled fires had become more common over time, citing larger village populations and more careless attitudes as causes of this change. Several collectors of thatching grasses and palms reported that these resources had become more difficult to find over time, due to an increase in uncontrolled fires. Others said that through experience and practise in burning for different purposes, environmental education about harms of fire (for example from NGOs), and fear of the law and fines, people had learned to be more careful and there had been fewer uncontrolled fires in recent years. However, the details of the law were in general poorly understood, and many also said that there were no laws or fines related to fire use.

Some respondents noted specific changes in ignitions: for example, claiming that there had been no fires to produce fresh growth for livestock until the Sukuma people moved to the villages. Hunting was also said to be less prevalent than it used to be, due to its criminalisation. In villages close to the Selous Game Reserve, people particularly feared being caught by game wardens and said there was little hunting in the village because of this. Hunting was a highly sensitive topic and only a few respondents across all villages discussed their own hunting activities openly; several respondents noted that trends in fire use for hunting were likely impacted by a range of variables. For example, some respondents reported lower availability of wild animals to hunt, compared with previous decades, reducing hunting activities overall. Many reported that although fire is useful for hunting larger game, some smaller species are best hunted in the rainy season and without fire. There was no correspondingly consistent reporting of changes to uncontrolled fires in living memory and remote sensing data showed no consistent directional trend in total area burned between 2001 and 2019 (Figure 4.1).

4.5 Discussion

These findings contribute to a growing body of research documenting how fires across sub-Saharan Africa are intentionally set by people in rural communities and important to local livelihoods. Many fire uses, such as for field preparation, livestock keeping (rangeland improvement) and honey collection, are common across multiple countries, communities and through time (e.g. Kikula 1986; Eriksen 2007; Shaffer 2010; Ribeiro et al., 2019b). In Kilwa, as in several of these studies, we found that it was often individuals or small groups who made decisions to burn, though elsewhere burning has also been found to be coordinated at the community level. For example, Butz (2009) reported that for the Maasai in northern Tanzania, burning was historically coordinated by elders to meet community needs, such as killing pests, keeping away dangerous wildlife and preventing late-season catastrophic fires, but also found that there has been a decline in this type of fire management.

The most common reasons for ignition reported in the study villages in Kilwa were useful to large proportions of village populations: for field preparation, clearing vegetation and debris around homes and farms, and clearing a safe path through grassland (Figure 4.3). The latter two of these intentions behind ignition were for direct protective or preventative purposes, mirroring some of the reasons for community burning cited by Butz (2009). However, respondents described the benefits of burning generally as relevant to the individual or small groups setting the fire only. Laris (2002) and Butz (2009) found that in communities in Tanzania and Mali, respectively, decisions to burn resulted in the creation of a landscape-level seasonal mosaic, which the authors argue is less hazardous and more useful than unburned land (though in Mali decisions to burn were not made communally). Here, in contrast, we found little evidence of the creation of a seasonal mosaic. A greater proportion of the land area burned in the later months of the dry season (Figure 4.1) when many risky fires were set, dictated by the livelihood activities carried out at this time (Table 4.2), and when conditions encouraged the spread of accidentally uncontrolled fire, which can be hazardous and harmful to people.

Fire seasonality in Kilwa shifted slightly from year to year (Figures 4.1 & 4.2), as was found by Cooke et al., (1996) in their study of fire regimes across continental Africa. Fire seasons in southern Africa tend to be consistent across areas with both high and low human influence (Archibald et al., 2010), suggesting that the shifting fire season is dictated by weather variations: grasses begin to burn when they are dry enough. In this study, we also found that year-on-year weather patterns (particularly timings of rainfall) altered people's decisions about when to set fire, i.e. people waited until the conditions are right for the kind of fire they want.

Fire management was therefore adaptive and responsive to environmental factors, such as rainfall seasonality, which could affect ignition decisions driving the fire regime in future, e.g. under projected increased rainfall intensity (Niang et al., 2014). Many respondents suggested that social and demographic shifts had influenced local attitudes towards fire, and potentially trends in the fire regime, yet recent fire trends were not perceived in a consistent way. For example, population growth was reported by some to have increased ignitions, whereas criminalisation of hunting and education from NGOs was claimed by others to have reduced ignitions. Fear of breaking the law by causing uncontrolled burns was also cited as a potential cause of reduced ignitions, though the details of the law were poorly understood. Tanzania's 2002 Forest Act requires people to seek permission before burning outside of their own land, but respondents were unaware of this and did not seek permissions prior to burning (though people with neighbouring fields often burned them together). Rather, decisions to burn for many activities, such as hunting, livestock keeping and to clear a path were made adaptively and often spontaneously.

The MCD64A1 Burned Area product we used here only goes back to 2001, which may not be a long enough time period to capture any possible trends in response to recent social drivers, for example the arrival of the Sukuma and increased use of fire for livestock keeping. These trends may also not be captured at the landscape-level by the 500 m pixel resolution of MODIS imagery, which misses small fires (Ramo et al., 2021). Comparisons across southern Africa show that high human population densities result in increased ignition frequency and reduced fire spread (Archibald et al., 2010), although the magnitude of the effect of human populations on burned area depends on local conditions (Andela et al., 2017). Even though trends in recent years are not observable at the landscape level in Kilwa, they could still affect local hazards and livelihoods in a meaningful way. For example, collectors of thatching grasses and palms reported that these resources had become more difficult to find over time, due to an increase in uncontrolled fires, resulting in a loss of income from these sources. Potential cumulative impacts of shifts in livelihoods and population sizes on fire regimes should therefore not be underestimated (Eriksen 2007; Butz 2009; Laris 2013).

Kull (2016) distinguishes between the roles of fire as a tool for rural livelihoods, a change agent transforming landscapes and a natural hazard. In this study, we found that the usefulness of fire as a tool understandably took precedence for people in Kilwa (as Kull also found in rural communities in Madagascar) and burning was optimised depending on the desired functioning of the land. Some land needed to be protected from fire (for example community forests) and other land had to be burned to be useful (for example some rangelands). The riskiest fires were reported to be those intended to spread uncontrolled, particularly for hunting and livestock keeping, which were usually set in dry and windy conditions (Table 4.2 & Figure 4.3). Although respondents generally described wider environmental and some social effects of uncontrollable fire as harmful, there is a trade-off between these potentially harmful impacts and the need to use fire for livelihood activities.

The widespread reporting of the harmful environmental effects of fire was likely influenced by national environmental narratives and teachings from environmental organisations, as also reported by Brockington (2006) and Gross-Camp (2017). Lovett (2003) argues that international conservation initiatives, such as Tanzania's participation in the Convention on Biological Diversity (CBD) and Reducing emissions from deforestation and forest degradation (REDD+) are highly influential of its national environmental policies, many of which frame fire as harmful. For example, in the National Biodiversity Strategy and Action Plan 2015-2020 (Government of Tanzania 2015) required by the CBD, fire is described as a major cause of biodiversity loss, and burning to prepare fields is labelled as ‘unsustainable’. Anti-fire policies in Mali (Laris 2002), northern Tanzania (Butz 2009), and Madagascar (Kull 1999) have been reported to encourage fires to be set anonymously, stifling community-level management and discussions about the best way to burn. Some respondents in this study suggested that environmental narratives may encourage secrecy in burning (EW and MM, pers. obs. 2019), though the data here are insufficient to determine whether this is a substantial issue. However, there was a clear tension between the belief that fires generally harm the environment and the concurrent belief that fire had long been a normal and acceptable part of the environment, supported by observations of land recovering from fires.

The fire management initiated by MCDI, prescribed burning used in some of the study villages in Kilwa, was related to community forests only. This type of fire management does not affect uses of fire for other activities and was considered successful by those involved. Elsewhere in Africa, community-based fire management, where attempted, has often had limited effectiveness (e.g. Dube 2013; Kilawe et al., 2021). For example, community-based fire management involving training, fire suppression, protection and monitoring, trialled in northern Tanzania, led to initial reductions in fire occurrence, but these were not sustained in the long-term. Kagosi et al., (2020) cite explanations for this including exclusion of community members from the process, limited training due to inadequate funds and the continued use of fire as a tool in activities like hunting, field preparation and honey collection. Fire management in this case undermined livelihood activities requiring the use of fire as a tool, and was therefore in conflict with the priorities of local people. Approaches in community-based fire management incorporating local knowledge, and an understanding of the importance of fire for livelihoods, are therefore likely to have better social and environmental outcomes. Aligning those outcomes in inhabited landscapes is likely to be one of the most important challenges for fire management in future.

4.6 Conclusions

This study is the first of its kind using data from interviews, focus group discussions and remote sensing to explore how human decisions drive different dimensions of the fire regime in a lived-in landscape in southern Africa. It is demonstrated that fire ignitions in Kilwa were driven mainly by human intentions, and that local people managed fire regimes in a way that served important livelihood needs. Most local people saw fire as a tool for achieving individual goals, as well as recognising its potentially harmful effects. Fire management was adaptive and responsive to environmental conditions, which are projected to change in future. Understanding how to align local priorities (including adaptive uses of fire) with conservation goals, must form the foundation for sustainable management of fire regimes in inhabited landscapes. Future field-based studies should explore the ecological impacts of the fire regime as driven by livelihood activities to better understand how to align those goals. Incorporating high resolution remote sensing (Ramo et al., 2021) would also improve understanding of the fire regime, as driven by livelihood activities, at a landscape scale in future.

4.7 References

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Chapter 5. Understanding the impacts of fire on wellbeing in rural south-eastern Tanzania using the capability approach

Home being built in Kikole village, Kilwa District, Tanzania (Ellie Wood, 2018).

Chapter 5. Understanding the impacts of fire on wellbeing in rural south-eastern Tanzania using the capability approach

5.1 Abstract

Decades of ecological research have explored the impacts of fire on African ecosystems, particularly in protected areas. However, similar academic attention has not been given to the impacts on the people who set fires and live with their repercussions each year. This research, based on 112 interviews and 27 focus group discussions in rural farming communities in south-eastern Tanzania, used the capability approach to study, for the first time, the impacts of fire on multiple dimensions of wellbeing. Respondents reported that a key overarching component of wellbeing is the freedom and choice to improve one's own life. Both controlled and uncontrolled fires were a means for improving wellbeing, particularly when used as a tool with a specific purpose. Fire was also a negative wellbeing converter, principally as a hazard unrelated to the original purpose, when it became uncontrollable, creating additional labour, economic losses, injuries, or even death, as well as fear associated with these potential impacts. Most respondents considered these hazards as sometimes-unavoidable risks related to activities necessary to achieving wellbeing aspirations (capabilities). This approach identifies fire impacts in rural communities and relates them to broader wellbeing goals. It can be used to identify where wellbeing goals could be maintained or enhanced and where negative impacts on wellbeing could be reduced, while means to achieving wellbeing may change, through fire management or other interventions. The finding, echoed in other empirical studies, that freedom and choice is a crucial component of wellbeing, supports calls for integrated fire management which does not undermine the agency of those who inhabit fire-prone ecosystems, and who depend on their environment to improve their own wellbeing.

5.2 Introduction

Research exploring the impacts of fire on the structure and functioning of African ecosystems (e.g. Kikula, 1986; Lawton, 1978; Ribeiro et al., 2019; Staver et al., 2011; Trapnell, 1959; Whelan, 1995) underpins formal fire management in protected areas whereby land managers aim to modify fire regimes. This is usually in service of specific environmental aims such as increasing biodiversity or reversing woody encroachment (Nieman et al., 2021). In recent years, there have also been discussions in academic literature about ways in which fire regimes could be managed to reduce carbon emissions (Lehsten et al., 2009; Ramo et al., 2021). Environmentally sustainable fire management is therefore a high priority for biodiversity conservation and climate change mitigation in Africa.

However, formal fire management has often failed to achieve its environmental goals (Trollope & Trollope, 2004). A major reason for this is that most fires are ignited by people who live in and around protected areas, using fire as a tool in activities such as field preparation, generating fresh grazing for livestock and honey collection (e.g. Hough, 1993; Eriksen, 2007; Butz, 2009; Shaffer, 2010). Research shows that poor integration of local livelihood needs such as these – even in cases of community-based fire management which actively engages local people – has resulted in failures to achieve the desired fire regime (Trollope & Trollope, 2004; Kagosi et al., 2020). Additionally, there are concerns that fire management which doesn't consider the uses and impacts of fire on local people will undermine local livelihoods and wellbeing. As a result, there are increasing calls for formal fire management to incorporate local values and interests, aiming for cultural as well as environmental sustainability, broadly termed 'integrated fire management' (Colombaroli et al., 2019; Meyers, 2006; Roos et al., 2016) which considers global concerns over biodiversity loss and carbon storage as well as local needs.

Recent political ecology analyses have explored the ways in which history and power dynamics shape local fire uses (e.g. Eriksen, 2007; Kull, 2004; Shaffer, 2010) and described some of the hazardous effects of fire (Kull, 2016), providing a richer understanding of the social role of fire in African communities. However, there have been no studies explicitly exploring the impacts of fire on local wellbeing. Understanding the relationship between nature and human wellbeing is fundamental to conserving and managing ecosystems for the benefit of current and future generations (Díaz et al., 2018; MA, 2003), and this gap therefore presents a major challenge for sustainable fire management.

The capability approach, pioneered by Amartya Sen and further developed by Martha Nussbaum and others (Sen, 1979, 1993, 1999; Nussbaum, 2000), is a theoretical framework that views human wellbeing in terms of people's valued functionings (realised achievements) and their capability (real opportunities) to achieve those functionings (Sen, 1993). The approach understands a good life as having freedoms to lead a life one has reason to value (Robeyns, 2017). Both capabilities and functionings are considered wellbeing ends (goals) (Sen, 1999). Sen has criticised analyses which focus on resources or the means to achieving wellbeing alone, such as wealth, because heterogeneity between individuals, environments and social contexts affect how people are able to use resources to live well (Sen, 1999). This heterogeneity is captured in the concepts of personal, social and environmental conversion factors (Robeyns, 2017) – the degree to which people can convert resources into wellbeing goals – which can also be considered means to achieving wellbeing goals. It is therefore important for any study of resources or means to living well, to be put in the context of relevant wellbeing goals.

An influential account of wellbeing aspirations and means to achieving them comes from the World Bank's Voices of the Poor research (Narayan et al., 2000a). The research found that while contexts and details vary, core dimensions of wellbeing amongst poor people are common across social and geographic contexts: 1) basic material wellbeing, 2) bodily wellbeing (health), 3) social wellbeing, 4) security, 5) freedom of choice and action. These domains were subsequently incorporated into the Millennium Ecosystem Assessment Framework exploring Ecosystem Services and Their Links to Human Wellbeing (MA, 2003). In these frameworks, freedom of choice and action spans the other four wellbeing categories, reflecting the capability approach: when real opportunities are present, then there is freedom to choose and act upon them to improve wellbeing (Narayan et al., 2000a). Other researchers have noted the importance of freedom and choice for understanding interactions between nature and human wellbeing, for example, whether people choose to plant trees or to cut them down (Polishchuk & Rauschmayer, 2012). Sen (2013) states:

> "We also have to go beyond the role of human beings specifically as 'consumers' or as 'people with needs', and consider, more broadly, their general role as agents of change who can—given the opportunity—think, assess, evaluate, resolve, inspire, agitate, and, through these means, reshape the world"

The capability approach is therefore a useful tool for understanding wellbeing-nature interactions and their inherent complexity. It can be used to evaluate positive, negative or neutral functionings and capabilities, and the ways that they may interact and trade-off (Abunge et al., 2013; Dawson & Martin, 2015; Polishchuk & Rauschmayer, 2012; Sangha et al., 2015). Here, I use the capability approach and insights from the dimensions of wellbeing identified by Narayan et al. (2000a) to evaluate such feedbacks between fire and wellbeing in farming communities in Kilwa, southeast Tanzania. In order to ground this analysis in the local context (*sensu* White & Ellison, 2007), I first identify local wellbeing goals (capabilities), and then assess the role of fire in wellbeing. I ask the following questions:

1. Which capabilities contribute to wellbeing in Kilwa farming communities?
2. How does fire act as a conversion factor i.e. a means to enable or inhibit achieving wellbeing goals?

5.3 Materials and methods

5.3.1 Study site and overview of methods

The study site was Kilwa District, in the Lindi Region of south-eastern Tanzania (sections 1.6 & 2.2). Interview data were collected from six study villages (Figure 2.1). Data on the uses and impacts of fire were gathered throughout data collection, totalling 112 interviews and 27 focus group discussions conducted in 2018 and 2019. Further details of these methods are given in the previous chapter of this thesis (section 4.3.1).

5.3.2 Focus groups discussions on wellbeing

The focus group discussions conducted during 2018 formed the foundation for understanding wellbeing goals and means in the study villages. Two focus group discussions, one with men and one with women, were held in each village in order to capture any differences between male and female experience (Narayan et al., 2000b). During these sessions, I first asked broadly about positive and negative contributions to wellbeing. Following discussion, I then asked about each of the five dimensions of wellbeing identified by Narayan et al. (2000a) in turn. For example, to identify factors related to social wellbeing I asked “are any aspects of your wellbeing linked to social relations and how you interact with people?” (Appendix 2). This allowed multiple dimensions of wellbeing to be discussed and compared across groups. Participants then worked together to draw a map of their village on paper, showing places important to wellbeing and where fires had occurred in the past 12 months. The cause and impacts of those fires were discussed, particularly in relation to aspects of wellbeing identified earlier in the discussion. The capability approach was not used as a framework during these discussions, but rather was employed during analysis based on the findings.

5.3.3 Analysis

NVivo 12 (QSR International, 2018) was used to thematically analyse interviews. A priori codes were set based on the five categories of wellbeing identified by Narayan et al. (2000a) while a posteriori codes about specific fire impacts on wellbeing emerged during data analysis. The process was iterative and involved several rounds of re-reading and re-coding interviews, following the practical approach described by Swain (2018). As Swain states (p. 5), this approach meant that “theory was both a precursor to, and an outcome of, the data analysis”. Issues that emerged as prominent guided the later rounds of analysis, during which capabilities and conversion factors were identified, as per this analytic approach.

5.4 Results

5.4.1 Wellbeing goals and means for achieving them

Themes around freedom and choice emerged as prominent during the early rounds of coding. Therefore the capability approach (in which freedom and choice are central concepts) was applied as a framework during later rounds of analysis. Table 5.1 shows examples of capabilities (wellbeing goals) identified from interviews and focus group discussions, and associated conversion factors (means which enable or inhibit achieving those goals). Several capabilities are also conversion factors. For example, having good mental and physical health were frequently explained as personal conversion factors enabling capabilities, but are also wellbeing goals in themselves.

There were no consistent differences between female and male focus groups. A recurrent and important theme across all groups was *moving up a stage in life* (Table 5.1) as opposed to *staying where you are* or *taking a step back in life*. I questioned these concepts from multiple angles during focus group discussions in 2018 and 2019, most explicitly when asking groups to consider whether a person born with all the things they would need to live a comfortable life could have a good wellbeing *by staying at the same stage in life* forever. Respondents consistently said that this would not result in living well. It was instead considered important to improve your situation, support your own family, gain more than you began with in life, and have autonomy and control over your wellbeing.

Table 5.1 (continues overleaf) Examples of capabilities and associated conversion factors impacting wellbeing in Kilwa District, Tanzania. Dimensions of wellbeing are shown in grey. Below each dimension is an example of an associated capability as well as social, environmental and personal conversion factors that either enable (positive conversion factors indicated by +) or inhibit (negative conversion factors indicated by –) the capability. *Freedom of choice and action* spans all wellbeing categories and associated capabilities. The arrow indicates the interconnected nature of these concepts so that different aspects of living well may be realised: when capabilities are enabled by conversion factors, there is real freedom to choose and act upon them, contributing to material, bodily, social wellbeing or security. These realised aspects of living well may then act as conversion factors themselves for other capabilities and aspects of wellbeing.

Freedom of choice and action
Capability: Being able to act on real opportunities to improve wellbeing and move up a stage in life. **Conversion factors** include all those related to the categories of wellbeing below. Important overarching conversion factors related to being able to move up a stage in life include the following: Environmental: + Land offers resources for healthy lifestyles and successful livelihoods (e.g. agriculture). − Natural hazards or a lack of resources. Social: + Infrastructure for a safe community, opportunities to learn, and opportunities to earn money. − Poor quality infrastructure, equipment necessary for livelihoods, social relations which limit individual success. Personal: + Being physically and mentally healthy, working hard, building good relationships with others. − Being ill or disabled, being lazy, or causing conflict.

Material wellbeing	**Bodily wellbeing**	**Social wellbeing**	**Security**
Capability: Being able to pursue successful livelihoods like farming, earn an income and have enough to feel satisfied. **Conversion factors** Environmental: + Fertile soils, enough rain. − Monkeys, other pests that steal crops.	**Capability:** Being able to be healthy and free of physical pain. **Conversion factors** Environmental: + Local medicines. − Environmental hazards of work e.g. smoke inhalation while making charcoal, enduring harsh conditions while hunting.	**Capability:** Being able to live in peace with your family and community. **Conversion factors** Environmental: + Shade under large trees where men congregate and play games. − Grasses insufficient for livestock so they eat crops, causing	**Capability:** Being able to gain knowledge provides security for the future enabling secure employment, and successful management of money, assets and natural resources. **Conversion factors:** Environmental: + Learning from the environment e.g. tree uses.

Social: + Transport and communication infrastructure to access markets and sell goods. − Insufficient farming equipment. Personal: + Ability and motivation to work hard. − Illnesses or disabilities that limit ability to work.	Social: + A hospital in the village, that you don't have to travel far to reach. − Hospital lacking electricity so medicines that need to be refrigerated cannot be stored. Personal: + Being fit and healthy. − Having an illness or disability.	conflict with farmers. Social: + A Village Office where conflicts can be resolved. − Poor phone reception limits communication. Personal: + Wealth to contribute to community development builds good relationships. − Having an unkind heart generates conflict, resentment.	− River flooding during the rainy season, children cannot cross to get to school. Social: + Schools in the village make it easier for children to access education and get a better job in future. − Children with many siblings may be less likely to go to school and get a smaller share of parental support. Personal: + Being intelligent and working hard. − Being lazy.

The importance of moving up a stage was partially explained as a way to mitigate risk and reduce dependence on others. It was thought that if a person was dependent on others for their wellbeing then wellbeing could be lost in a way that was beyond their own control if, for example, parents die and cannot support their offspring any longer:

> "No matter how, no matter what, every person who is born… you need to struggle for a better life. Because today you can rely on your parents, and you have some siblings around you, who you might fight with after your parents die. So still you need to be able to fight for those things yourself and move from one stage to another." (Respondent during ranking exercises for non-committee members in Kikole, 2019)

Several respondents suggested that some people are lazy, dependent on parents, and content to stay at the stage they find themselves in life. However, none of the participants considered that they themselves would live well in this way, even if they had enough for a comfortable life. Participants emphasised the fluid nature of life, progression through stages from dependence to responsibility, being a good citizen and having one's own dependents. Wellbeing was therefore not simply defined by having things, having enough or by maintaining a certain level of comfort, though these things were considered important. Participants had aspirations to thrive and contribute to the wellbeing of others including their children, in contrast with a static concept of survival or having enough.

Several capabilities and personal conversion factors, such as having knowledge, working hard, having the spirit to improve one's life, were discussed as crucial means of living well, having security for the future, and moving up a stage in life. I asked groups "If two people have the same wealth and assets, can they have different levels of wellbeing?" All respondents agreed that one could live in a better way than the other, and it was considered that individual circumstances, ability and autonomy that determined this. Natural resources, assets and wealth were all considered vital to wellbeing but did not automatically grant it. How a person acted and used these conversion factors mattered:

> "There are some people who have a lot of wealth but don't know how to use it. You can be poor, but maybe you don't want to work hard, you are just there… Money doesn't make you work hard – it's just your spirit. What remains is working hard and nothing more. If you work hard it's your capital for your life." (Respondent during male focus group discussion in Mtyalambuko, 2018)

> "There are two different types of rich people – those who save and think about their future, and those who just spend their money straight away in bars drinking… Because, sometimes you can be investing and saving for your kids and your home, so this can help your family when you are gone. If you just use the money without saving, it can be horrible for your family later." (Respondent during female focus group discussion in Ngorongoro, 2018)

There was a general feeling that life in the study communities is a struggle compared to the lives of some outsiders or rich people, and therefore the emphasis on moving up a stage may have emerged partly from feelings that people in the village generally do not have enough, and their lives demand hard work in order to have enough and survive. However, having the spirit to work hard and improve one's own wellbeing clearly also had inherent and moral value, and was related to being a good citizen and a provider for the family.

5.4.2 Fire as a wellbeing conversion factor

Fire can be most straightforwardly categorised as an environmental conversion factor related to several capabilities (wellbeing goals; Table 5.2), though it has personal and social controls i.e. people who set and suppress fires control their impacts to some extent. Most fires were ignited by individuals and small groups for various purposes (see Chapter 4 of this thesis), and fire was often described by respondents as a basic need, increasing the usability of land for agriculture, livestock keeping and hunting, acting as a tool to increase security and ease labour and other activities. Success in the livelihood activities supported by fire and, often, the opportunity to pursue several means of generating income, was seen to be how people move up a stage in life and improve their wellbeing.

However, the costs felt when homes and crops burned - money, labour, time and resources used to rebuild property, or buy food – were ways that fire could cause someone to take a step back in life:

> [Do you think that fire influences your wellbeing?] "If fire comes to your home it causes many harms. You won't move [in life]" (Respondent during female focus group discussion in Mtandi, 2018)

> [If there was more or less fire in future would it impact your wellbeing?] "If [negative] fire issues decline it will help improve your life because you don't have immediate expenses of rebuilding homes, losing fruit trees. If [negative] fire issues increase, you will stay where you are [in life]." (Respondent during female focus group discussion in Kikole, 2018)

Many of the negative impacts of fire were not felt financially, but generated (economic) costs in the form of labour required to repair the damage caused by fire (Table 5.2). Fire also generated feelings of fear and frustration, and in extreme but relatively rare cases, fire was reported to directly injure or kill people. Almost all of these negative impacts of fire were felt by people who did not have control over the fire (either because a fire became uncontrollable accidentally, or because someone else had chosen to set a fire which became uncontrollable), while many of the benefits were gained by those in control of the fire.

Some of these capabilities (and related fire impacts) are strongly linked to particular wellbeing dimensions, but many dimensions are interrelated. For example, being able to live in a home that is secure, clean and beautiful is a capability directly linked to material wellbeing and security, but could also be linked to bodily wellbeing (enabling physical safety) and social wellbeing (enabling good social relations between household members). Freedom of choice and action spans all wellbeing categories and is therefore linked to all capabilities, but in particular is directly associated with being able to improve wellbeing and move up a stage in life.

Table 5.2 Perceived capabilities (wellbeing goals), and the related role of fire as a positive or negative conversion factor which enables or otherwise inhibits corresponding wellbeing goals in Kilwa District, Tanzania.

Capability	Positive conversion factor	Negative conversion factor
Being able to live in a home that is secure, clean and beautiful	Controlled fire used by men and women to clear away flammable grasses, weeds and other debris in the land around homes. This both reduced risk of uncontrolled fires reaching homes later in the fire season and made the area clean and presentable.	Uncontrollable fire which damaged or completely destroyed homes in the village centre and secondary homes occupied when families are working at farms further away during the rainy season. These secondary homes were usually made only of grasses, surrounded by other fields or grassland areas that burn, and were not occupied during the height of the fire season, which made them more vulnerable to unexpected fire.
Being able to pursue livelihoods successfully, to earn an income and have enough to feel satisfied		

- **Grow good crops to eat and sell**	Controlled fire used by men and women every year during field preparation before crops could be planted: to clear weeds, debris or trees and other vegetation if a new field was being established. Burning was often planned in collaboration with owners of neighbouring fields so that multiple fields could be burned effectively at the same time. Controlled fires set by men and women around the perimeters of fields and around fruit trees reduced the risk of uncontrolled fires spreading between fields and destroying crops. Bonfires used by men and women to keep away crop-eating pests and increase yields.	Uncontrollable fire which accidently burnt fields before the owner (male or female) was ready created frustration and additional work. This often happened because a farmer with a neighbouring field burnt their land without warning. Soil that had been repeatedly burnt was said to lose fertility and harden so that crops would not grow well here. Most crops were harvested before the fire season, but fires outside of the main season could burn growing crops, and uncontrollable fire at any time could burn stored food. Fruit trees were valuable cash crops and were vulnerable to fire throughout the year; incomes suffered if trees burnt because it took one or more years for more fruits to grow again.
- **Keep livestock to eat and sell their milk and meat**	Fires set in chosen areas by (usually male) members of the Sukuma tribe and left to burn uncontrollably encouraged grass regeneration to feed livestock.	Uncontrollable fire burnt away good grasses needed to feed livestock.

	Controlled fires used by (usually male) members of the Sukuma tribe to create fire breaks and protect palatable grasses. Bonfires used by (usually male) members of the Sukuma tribe to keep predators away from livestock.	
- **Hunt wild animals to eat and sell their meat**	Male hunters set fires which were left to burn uncontrollably to increase visibility, create fresh grazing to attract game, and chase animals towards grazing grounds and traps.	
- **Collect honey to eat and sell**	Controlled fire was used to smoke out bees during honey collection, which is usually conducted by men.	Uncontrolled fire occasionally burnt bee hives.
- **Make charcoal to sell**	Controlled fire set inside earth kilns was used (usually by men) to make charcoal from cut logs.	Smoke inhalation from charcoal making could be unpleasant and bad for health.

- **Collect natural resources such as logs, grasses, and local medicines all of which may be used for subsistence activities or sold**	Men and women set uncontrollable fires before passing through a grassland area to access resources, improve visibility and ward off dangerous animals such as snakes. In the study villages with community forest management, those (men and women) involved reported that prescribed burning around the borders of the community forest has successfully reduced later uncontrolled fires entering the woodland. This protected timber species, which could potentially generate funds for the communities. However, those respondents who had not been involved in community forest management or prescribed burning were less sure of the effectiveness of this intervention.	Uncontrollable fire burned resources, particularly non-woody resources such as herbaceous medicines used by witch doctors (men and women), grasses used for roof thatching, palm leaves used to make mats or roof thatching, or cut logs to be sold. In most cases, these resources could be collected elsewhere but this created additional labour and frustration. Good quality grasses could be difficult to find and if fire came early in the dry season and destroyed the grasses then they may not regrow for many months and the opportunity window for collecting grasses was reduced.

Being able to be healthy and free of physical pain	Fire eased physical labour in some instances, for example in hunting for men, and clearing fields before planting crops for men and women.	Uncontrollable fire could injure or kill people. Smoke inhalation and extreme heat from uncontrollable fires could be unpleasant and harmful. Uncontrollable fire could create additional physical labour if a man or woman's field was burned before desired, or when resources were hard to find because many had burned.
Being able to feel relaxed and safe	Uncontrollable fires set by men and women to burn a pathway through grasses increased visibility of dangerous animals like snakes so that a person could pass safely. Controlled burning by men and women around homes, fields and fruit trees minimised the risk of uncontrollable fire burning these important places later.	Uncontrollable fires could be dangerous and scary.

Being able to look after the environment, for now and for future generations	Uncontrollable fire enabled some fire-adapted plant species to grow.	Uncontrollable fire could kill animals or destroy their habitats and food. Repeated uncontrollable fire could destroy the trees and make the area turn to grassland. Wet wood and large trees were not vulnerable to fire, but damaged trees and herbaceous parts of plants were.
Being able to have good relationships in the community		Uncontrollable fire could cause or exacerbate conflict if one person set a fire that harmed another such as by burning their home, crops or other possessions.

Being able to improve and move up a stage in life	Both controlled and uncontrollable fires were an important part of many livelihood activities for men and women including growing crops, livestock keeping, hunting, honey collection and charcoal making. Many chose to participate in more than one of these activities as this was a good way to increase wealth and have a more stable flow of income and resources to support the family. For example, honey was an important foodstuff if a farmer's crops fail, and charcoal making could supplement income from agriculture.	Uncontrollable fires burned property like homes and crops. Repairing property, and replacing food resulted in costs of time, labour and finance. Some were injured or died in uncontrollable fires.

5.4.3 Freedoms and choices determined the costs and benefits of fire

Both controlled and uncontrollable fires brought benefits (Table 5.2). Generally, those benefits were seen by respondents as accruing only to fire users, who had a specific purpose for doing so. For example, most direct benefits of uncontrollable fires used in hunting and livestock keeping were felt by small groups involved in those activities – usually men in both cases, though the families of these men also benefited from hunting and livestock rearing activities. Only members of the Sukuma tribe kept large livestock.

Fires which, intentionally or otherwise, became uncontrollable had sometimes impacted members of the community who were not responsible for igniting the fire. Almost all harms came from fires that were uncontrollable and therefore likely to be unexpected, more intense and spread further (all aside from smoke inhalation when making charcoal, or potential reductions in soil fertility, Table 5.2). Those impacts, for example if homes or crops were burned, were usually negative and unrelated to the original purpose of the fires:

> "Fires are set for people's own purpose. There's no benefit if you haven't set the fire. But there may be harms." (Farmer in Mtandi, 2018)

> "If negative fire issues decrease the village will be in a better place, there will be peace. We need fire. It's a basic need, so if there's no fire it would be a problem. But if accidental fire and wildfire decrease, it will be good for us." (Farmer and honey collector in Kikole, 2018)

Fire was therefore likely to contribute to the wellbeing of the person setting it, but had the potential to negatively impact the wellbeing of others. The negative impacts could be widespread; for example, if grasses useful for roofing were burned, then this could be a loss for many people. Therefore individual freedoms and choices related to the fire purpose and the degree of control fire users or others had over it, were important determinants of fire impacts.

5.4.4 Everyone is vulnerable to fire hazards, but some are more vulnerable than others

Some fire hazards were reported to come from domestic sources, but others came from uncontrollable bushfires. These fires had the potential to affect the entire community, but how, when, and where fires were set dictated their extent and severity (chapter 4) and some people and places were more vulnerable to the hazardous effects of fire (e.g. Table 5.2):

> [Who is most affected by wildfires here?] "People who have not cleaned [burnt away flammable debris from] their fields. If the field is dirty it can be burned and cause some harms for them. The second people are those using grassland areas and forest areas to survive, those people who have homes that are covered in grasses, if the roof catches fire they will suffer" (Farmer and small business owner in Kikole, 2018)

I spoke to five women who collected grasses sold as roof thatching to earn money on top of their farming activities. They collected grasses from June – after the rainy season and the busy farming period – until all the good grasses were burned away. This was usually August but could be November in years with little fire. All described being unable to collect grasses from specific areas because fire had burned them away, which resulted in frustration, more work to find grasses, and loss of income if those grasses could not be found until next year. If there were no grasses available for roof thatching, those who could afford it bought coconut leaves (*makuti*) for thatching instead of buying or collecting their own grasses.

Some people made mats from palm leaves (*ukili* and *ukindu*) to use and sell. One woman who bought or collected the leaves said she had travelled further to find leaves in recent years, as more were burned compared to previous years. Others continued to collect palm leaves in the village, but also sometimes found that they were burned. Selling grasses and mats were activities often, but not always, carried out by women. I met one man who plaited palm leaves for roof thatching because he had reached an age where he was physically unable to farm, which had previously been his primary livelihood activity. It was the poorest who used palms and grasses rather than tin for roofs. Groups like women, the elderly and the poorest were therefore likely to feel the worst impacts from the burning of palms and grasses.

5.4.5 Perceptions of fire hazards

Fires with a legitimate purpose (usually related to livelihood activities or safety) were often said to occur in places that are supposed to burn; this was thought to be using fire in a good way, as opposed to using fire in a bad way:

> "If you are using fire in a bad way in a place that shouldn't be burned then it has harms. But if you are using it in the right place in the right way then there's nothing to fear and there are just good impacts of fire, on the environment and you." (Farmer and carpenter in Ngorongoro, 2018)

> "If you use fire in a good way, it will come back to you in a good way. If you use fire in a bad way, it will come back to you in a bad way." (Farmer and witch doctor Mtandi, 2018)

If fire was used in a good way or somewhere that was supposed to burn, then most people considered associated fire hazards as a sometimes-unavoidable consequence of necessary activities. For example, when fires used to clear fields went out of control, often this was not thought to be the fault of the person setting the fire, but due to factors that were difficult to predict and control like a sudden increase in wind speed. The respective roles of human and environmental causes of uncontrolled fire could be difficult to tease apart and many felt empathy and understanding that next time it could be their own fire that went out of control:

> "We are living in a peaceful way, one day someone can cause the problem, but the next day you can cause the problem so we forgive each other." (Respondent during ranking exercises for committee members in Mtyalabuko, 2019)

Some more readily assigned blame to those allowing fires to go out of control:

> “Sometimes people aren’t careful enough when setting a particular fire, in a field or anywhere.” (Farmer, honey collector and hunter in Mtandi, 2018)

> “Farmers don’t have knowledge… they can set fire without any reason and without controlling it… In some areas like where there are fruit trees they will try to control the fire, but in fields they won’t.” (Farmer and carpenter in Ngorongoro, 2018)

Generally, if the fire was set for reasons considered legitimate like field preparation, then negative consequences were more likely to be acceptable. The benefits of using fire as a tool in these circumstances were more certain and more common than the risks. Uncontrollable fires, too, could be useful (Table 5.2) but there was less agreement about good impacts of intentionally uncontrollable fires such as for hunting and livestock keeping. Uncontrollable fires caused by carelessness, such as someone dropping a cigarette, were not acceptable because these fires were not associated with benefits, only risk.

Ultimately, the necessity to use fire as a tool was often prioritised despite associated risks or perceived wider negative impacts of fire on the environment. We discussed this with one respondent who believed that using prescribed burning to protect the community forest from later fire was important to conserve the valuable timber species inside, to bring benefits to his village. However, he still collected the high quality resources found in the reserve for his own use, and set fire inside if he needed to:

> “You can enter the reserve and see thick grasses, and then you know it’s a place for dangerous animals and you set fire as usual.” (Farmer and small business owner in Kikole, 2018)

The long-term biophysical effects of fire (for example, the perception that repeated uncontrollable fire would kill trees and turn the area to grassland) were generally perceived as negative though many of these effects were reported as having been taught by school teachers, NGOs, *Bwana Shamba* or *Bibi Shamba* (government employees who lived in the villages to educate and assist local farmers; terms used for men and women, respectively), or as being simply well-known in general rather than directly observed (chapter 4).

5.4.6 Preventing fire hazards and coping with losses

Men and women prevented fire hazards by burning or digging fire breaks in important places such as the village centre (Table 5.2), and this was considered a personal responsibility. If a fire reached the village, water and green branches (*mafukutu*) were used to extinguish it. Burning agricultural debris in piles rather than burning the whole field was seen as a way to prevent damaging impacts of fire on soils, and this was taught by *Bwana Shamba* or *Bibi Shamba*. Diversifying livelihoods was seen as a way to cope with fire hazards. One carpenter told us about the importance of his other livelihood activities when some of his timbers burned:

> "The first fire caused me some damages – 11 pieces of timber were burned, which had cost a total of 65 000 [TZS ~30 US$]. I went bankrupt, but later recovered. The next fire burned almost 25 pieces of timber – I could make two and a half beds from these, so it was bad for me. Though I wasn't doing carpentry alone, I had other issues [livelihood activities] too so I recovered again. The second time I lost 175 000 shillings [~75 US$]…" [What were the other activities that kept you afloat?] "Farming, roof making too." (Farmer, carpenter and roof maker in Kikole, 2018)

Those who burnt someone's crops or home sometimes paid compensation. However, there was no formal mechanism for payments, and most issues were more likely to be resolved between neighbours rather than through the Village Office or another official channel. Often, there was no payment. Reasons reported for the lack of payment included: compensation seemed futile because it would never be enough to cover the damages; everyone set fires and therefore accepted risks and hazards associated with this; it was seen as the owner's responsibility to protect their property from fire; and, so that peaceful relationships in the village would be maintained. One man whose crops had been lost to fire explained why he hadn't created a fire break around his field and had not sought compensation:

> "I never reported it to the government because they will say that I didn't create a boundary to protect my field."… [Do you protect your field from fire?] "It's a big

> field, so to dig a boundary is very expensive. The force of fire can be very big even if you do put a big boundary around the field – fire can spread.” (Farmer and carpenter in Mtandi, 2018)

Many emphasised that they lived in a good way or like one family in their village. To ask for payment to compensate for a ‘normal’ mistake was considered unkind. Being a good neighbour and part of the community involved forgiveness for these mistakes:

> “There isn’t compensation and we are living like one family here. Today it is one person, and another day it might be your turn. So if you are going to pay, who are you going to pay? And even if you don’t know the person, it’s normal and there’s no compensation.” (Respondent during ranking exercises for non-committee members in Mtyalambuko, 2019)

> “If you have a bad heart you can make someone pay you. But if you are good enough, you can just forgive.” (Female farmer and witch doctor in Mtyalambuko, 2018)

Often, fire hazards had anonymous causes. Uncontrollable fires were usually discovered far from their source, and may have been set anonymously and intentionally because of the perceived or real negative impacts they may have on people and the environment:

> “You can’t determine someone’s mind. You can be together, and then later they can go to a bush and set fire in secret way” (Respondent during ranking exercises for committee members in Mtalambuko, 2019)

> “You can’t know the person who has set fire, it’s just a normal human who has decided to set fire in grassland.” (Witch doctor in Mchakama, 2018)

This anonymity reinforced the lack of expectation for any compensation or resolution:

> “You don’t know the person who set fire so there’s no one to quarrel with.” (Female farmer and grass collector in Kikole, 2018)

> "We didn't know who started the fire so we rebuilt the home [that burned] and kept quiet" (Female farmer and small business owner in Kikole, 2018)

For many the losses caused by fire were felt significantly but, without someone to blame and pay for the damages, many bore the majority of this burden themselves. However, other members of the family and neighbours (who were not responsible for the fire) were likely to donate money or other resources needed. One man reported that when his home made of grasses had been burned because of children playing with matches, people gave him donations of clothes and money. Another woman whose home had recently burned because of an electrical fault said that no-one had helped because her husband was not yet home, but expected help when he returned.

5.4.7 Fires as a means to achieving wellbeing goals, but not an end in itself

Fire was seen as a tool to achieve specific goals and not an end, or wellbeing goal, in itself. Some hoped for alternatives to fire for many activities, as this was seen as a way both to reduce fire hazards and to improve the success of activities. For example, there was a feeling amongst some honey collectors and farmers that fire isn't the best tool for their activities, but people could not afford the alternatives like bee smokers (a small device used to smoke bees out of their hive) and farming machinery. When one farmer was asked if it's important to burn, he said:

> "No, we are destroying the area. But we can't afford to cultivate another way – we have to use fire." (Farmer in Mtandi, 2018)

For other activities such as livestock keeping and hunting, clearing a good path through the forest, an alternative to fire was less plausible. We asked one hunter if it was difficult to hunt without fire in the dry season. He said:

> "You can hunt but in a very difficult way. You need fire no matter what and no matter how." (Farmer; former blacksmith and hunter in Mtyalambuko, 2018)

5.5 Discussion

The findings here related to the overarching dimension of wellbeing: freedom of choice and action (MA, 2003; Narayan et al., 2000a), and particularly the importance of the capability to act on real opportunities to improve one's own wellbeing and move up a stage in life, highlight the aspirational nature of wellbeing established in other studies (Dorward et al., 2009). For example, during their research in Kenyan fishing communities, Abunge et al. (2013) found that components of wellbeing related to freedom and choice were valued highly. Respondents cited having a developmental mind – the aspiration and ability to improve one's own life – as important to living well.

In their study of two villages in central Tanzania, Östberg et al. (2018) found that shifts in personal attitudes and particularly greater motivations to work hard were reported by respondents as reasons why family wealth had increased in the study villages between the 1990s and 2016. People perceived a direct link between their work ethic and efforts and having the financial means to improve one's own life. In the present study, respondents reported that personal conversion factors such as being physically and mentally healthy, and working hard, determined whether someone would be able to move up a stage in life. While multiple social and environmental conversion factors also limit or enhance people's ability to move up a stage in life, or improve their own wellbeing (Table 5.1), personal aspirations and choice are therefore considered crucial components of a good life in many communities.

In the study villages there were several fire-based livelihood activities, and it was the contribution of these activities to wellbeing (allowing people to eat, live in safety and comfort, and earn money which may allow them to support a family and move up a stage in life) that motivated people to burn. Fire can therefore be understood as an environmental conversion factor which, as fires are ignited and controlled by people, intersects with personal and social dimensions (Table 5.2). Fire use was described by respondents largely in practical terms – a means to wellbeing goals – and for activities where there may be plausible alternatives (such as using machinery rather than fire to clear an agricultural field), respondents were open to, sometimes eager for, alternatives. As Kull (2004) also reports in

Madagascar: fire, then, is part of culture, but it is livelihoods rather than culture that explain why people burn.

Both *freedoms to* (e.g. achieve what you want to achieve), and *freedoms from* (e.g. fear and uncertainty over the future) are important to living well (Wood, 2007). In this study, fire enabled freedoms to principally through livelihood activities, but also contributes to the freedoms from aspect of wellbeing. For example, burning a path in grasslands enabled freedom from dangerous wild animals, and burning to remove flammable material enabled freedom from the risk of late season fires burning property. However, uncontrollable fires also generated fear and were a real threat to people, their property and resources. Some capabilities related to the use of fire therefore traded-off with others (Robeyns, 2017), for example if one person used fire to improve their wellbeing (e.g. by enabling their freedom to pursue livelihoods) and this decreased someone else's wellbeing (e.g. by reducing their freedom from harm by fire). Purpose and control over fire – factors related to the freedom and choice of both the fire user and any person impacted by the fire – therefore determined the costs and benefits of fires for different people.

As is clear from the continued use of fire in many rural communities (Hough, 1993; Butz, 2009; Shaffer, 2010) the need to use fire as a tool often outweighs its role as a hazard, with fire intention and benefits often justifying potential costs (Kull, 2016). In this study, potentially hazardous side effects from fire were more likely to be accepted if the purpose of the fire was considered legitimate – especially fires which met livelihood needs, with some livelihood activities being more acceptable than others. It is possible that more acceptable livelihoods were simply those which were more common and had longer histories in the study villages e.g. uncontrolled fires associated with field preparation were more likely to be forgiven than uncontrolled fires caused by livestock keeping.

Attitudes towards fire risk therefore did not depend only on the potential impacts of those risks, but on whether risks were seen as morally justifiable. In a study of perceptions on prescribed burning in Australia, Altangerel & Kull (2013) found that perspectives were shaped not just by perceptions of the actual impacts of fire, but also by whether exposure to fire risk was thought to be voluntary or involuntary, with involuntary risks seen as less morally justifiable. For example, some were against prescribed burning even if this could reduce fire hazards because they perceived resultant negative impacts on wildlife as involuntary (wildlife did not choose to be exposed to the prescribed burn) whereas people living in fire-prone areas were seen as exposing themselves to risks voluntarily. These findings highlight the important role of personal ethics in perceptions of fire impacts, across different cultural contexts. Many respondents in Kilwa emphasised the importance of individuals observing practices to control fire and minimise hazards. Further, even those hazards which were deemed more acceptable from the perspective of the people exposed to them, threaten wellbeing, and so should be considered harmful (Nussbaum & Sen, 1993).

The influence of environmentalist narratives on peoples' perceptions that fire is harmful to nature was discussed in the previous chapter of this thesis. For example, respondents reported that fire reduced soil fertility (Table 5.2). In this chapter I also reported that stewardship – being able to look after the environment, for now and for future generations – was considered a wellbeing end by respondents (albeit, this is a capability that may not be valued as highly as immediate needs). Recent capability approach literature has interpreted or applied the approach to environmental sustainability. Perhaps the most fundamental link between these concepts is discussed by Holland (2008) who notes that because environmental sustainability (or sustainable ecological capacity) is necessary for all human capabilities, it should be considered a meta-capability. Sen (2013) also argues that sustainable development should be understood in terms of sustaining human freedoms:

> "With this freedom-oriented modification, we can see 'sustainable development' as development that prompts the capabilities of present people without compromising capabilities of future generations."

Therefore, to assess the sustainability of the fire regime in Kilwa, an understanding of how fire affects ecological, economic and social systems and how these systems may change to enhance or limit the capabilities of future generations is also required (see Lessmann & Rauschmayer, 2013). Key questions relate to the carbon emissions generated by the current fire regime, what kinds of lives and livelihoods the land will be able to support in future, and how fire impacts biodiversity. For sustainable fire management, these long-term fire impacts (which affect the capabilities of future generations) must be balanced against understanding how fire impacts the capabilities of current generations, as demonstrated in this study. For example, while fire is necessary for maintaining grassy ecosystems and the services they provide in the long term (Veldman, 2016), excessive fire on an annual basis could deplete herbaceous resources used by current populations.

5.6 Conclusions

Most formal fire management in Africa has typically had ecological rather than social goals. While in recent years there has been increasing recognition of the important role of fire in human livelihoods, this is the first study to explore the impacts of fire on multiple dimensions of wellbeing. This study shows that the capability approach and its focus on human freedoms is a valuable tool for understanding fire and the ways it both contributes to and undermines human wellbeing. By differentiating between wellbeing means and goals in the assessment, this approach can be used to identify ways in which the fire regime can be managed to enhance wellbeing goals and limit its negative consequences. Wellbeing for local people can be maintained even if the means to achieve them change; for example, improved farming equipment may reduce the need to use fire in field preparation. Understanding of the long-term effects of fire, and therefore its impact on the capabilities of future generations, is also required to assess the sustainability of the fire regime. This study also supports numerous empirical findings that freedom and choice are crucial components of human wellbeing. It finds that personal control over fire is strongly related to its positive and negative impacts. This supports calls for integrated fire management which meaningfully engages local people and maintains the freedoms and choices of those living in fire-prone ecosystems.

5.7 References

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Chapter 6. Discussion

Site of recent uncontrollable fire in Kikole village, Kilwa District, Tanzania (Ellie Wood, 2018).

Chapter 6. Discussion

6.1 The importance of case studies investigating fire causes and consequences

In 2007, a global analysis based largely on expert opinion reported that >70% fire regimes across the world's terrestrial tropical regions were categorized as 'degraded' or 'very degraded' in relation to biodiversity conservation (Shlisky et al., 2007, 2009; Figure 6.1). These fire regimes – including those in the entire miombo region – were considered to be outside of their range of natural variation, with degraded regimes thought to be restorable while very degraded regimes may not be restorable. The most widely attributed causes of changes to tropical fire regimes were: "climate change, agriculture and ranching, deforestation, rural and urban development, energy production, fire exclusion and suppression, invasive species, plantations, and arson" (Shlisky et al., 2009).

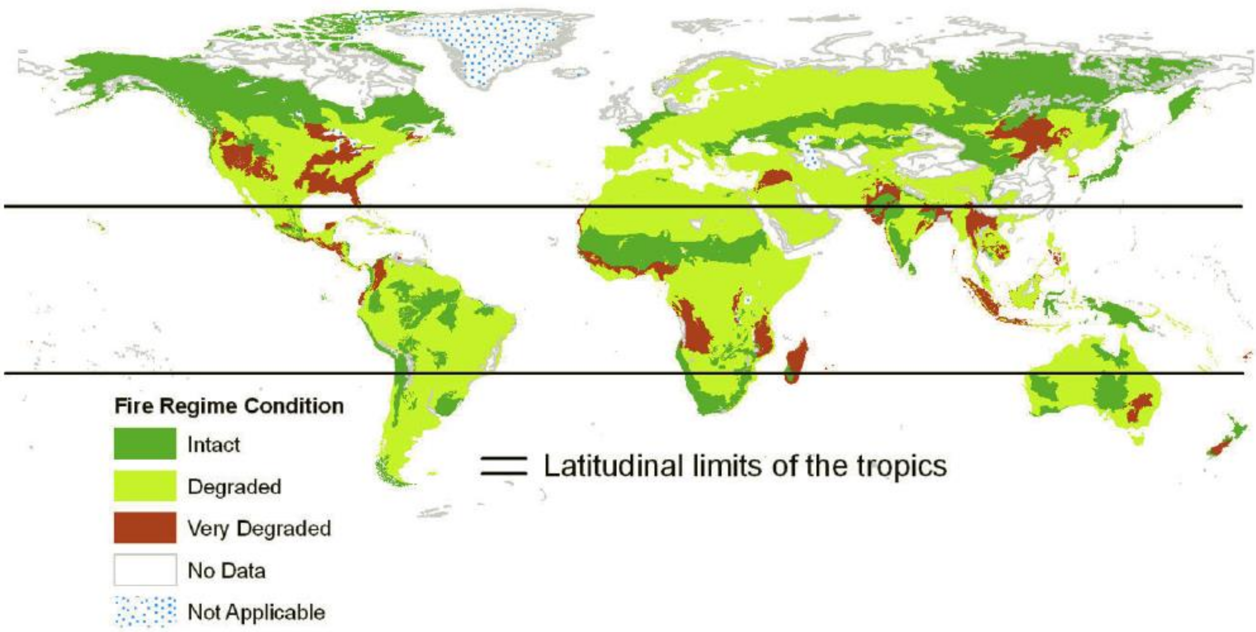

Figure 6.1 Global distribution of fire regime conditions reported in Shlisky et al. (2007, 2009). 'Intact' fire regimes include those that are considered by experts to have regime characteristics (e.g. frequency, severity, extent, and season) within their range of natural variability. 'Degraded' regimes are to be outside their range of natural variation, but restorable. 'Very degraded' regimes are those far outside their natural range of

variability, and may not be restorable.

This analysis highlights the global significance of fire regimes, draws attention to fire issues common across regions, enables comparisons with other global datasets to identify regions of overlapping concern, and points to potential priority areas for fire research and management. However, Shlisky et al. (2007, 2009)'s coarse-resolution overview also masks variation in local contexts, while elevating the perspectives, values and interests of those contributing expert opinion and analysis to the production of the map over those living the realities it represents (Wyborn & Evans, 2021). As the authors recognise, to identify the causes and consequences of fire regimes within a given context demands a more nuanced approach, using empirical evidence beyond expert opinion.

Shlisky et al. (2007, 2009)'s analysis reflects the views of conservationists. Several of the major causes of fire regime degradation cited by the contributing experts are related to fire management conducted at the local level, for example agriculture and livestock ranching, charcoal production. Some of the most important perspectives omitted from this analysis are therefore those of the local experts who live with and use fire. To understand fire regimes and move towards informing management strategies, we need to know the ways in which farmers, livestock ranchers, charcoal producers, and others in the community consider the fire regime useful, harmful, or both.

In this thesis, I used a case study approach to explore some of the complexities surrounding fire regimes that can only be understood at much higher resolution than a global analysis. In this final section, I synthesise the findings from the empirical chapters and place them in context of the wider literature. I begin by summarising the main findings from chapters 3–5. Then, I discuss how these research findings address my research aim to assess causes and consequences of fire, their synergies and trade-offs, and I answer the question 'does fire cause degradation in my study site?'. Finally, I discuss how these findings can inform fire management in southern African woodlands.

6.2 Summary of main findings

In chapter 3 I report an overview of tree demographic rates across Kilwa District and explore variables related to tree growth and mortality, based on the resurvey of a network of woodland plots consisting of ~1700 stems at 12 locations. Data were collected on large diameter (≥40 cm diameter at breast height) stems because large trees are keystone structures in miombo ecosystems disproportionately influencing biodiversity and carbon storage, but long-term studies exploring their demographics and potential threats are rare.

I found no evidence of a directional change in biomass or diversity: Kilwa's woodlands were stable over a period of nine years, with mortality being offset by stem growth and recruitment. On average, large stems stored 10.9 ± 5.1 (SD) tC ha^{-1}. The results from modelling and focus group discussions suggested that wounding, over-harvesting, and fire constrain individual growth and/or survival of large diameter stems. Fire reduced growth – with annual burning estimated to reduce dMAI by 1.12 ± 0.43 (SEM) mm yr^{-1} – but did not increase mortality of large trees.

In chapter 4, my co-authors and I aimed to identify the main causes of fire, and the extent to which human ignitions and intentions drive the resulting fire regime. We reported findings from interviews and focus group discussions in six villages, combined with remote sensing.

We found that the most common ignitions were intentional and important to livelihoods. Burning was adaptive, responsive to environmental conditions, and optimised for the intended outcome with the perceived riskiest fires intentionally spreading uncontrolled. Most of the total burned area was accounted for by fires during the late dry season when people burned for activities such as field preparation, and when environmental conditions encouraged fire spread. The fire regime, dominated by late dry season fires, was therefore largely driven by the intentions of individuals living in the study villages.

In chapter 5, the final research chapter, I aimed to qualitatively explore the consequences of fire on multiple dimensions of local wellbeing. I analysed data from interview and focus group discussions to establish wellbeing goals in the six study villages and identified the impacts of fire on these goals.

I found that wellbeing goals in Kilwa span five dimensions common to people around the world (Narayan et al., 2000): 1) basic material wellbeing, 2) bodily wellbeing (health), 3) social wellbeing, 4) security, 5) freedom of choice and action. Importantly, freedom and choice – encapsulated in the aspiration to move up a stage in life – was key to wellbeing. As a result of this finding, I used the capability approach to identify the ways in which fire acted as a conversion factor i.e. a means to enable or inhibit achieving wellbeing goals. I found that both controlled and uncontrolled fires were a means for improving wellbeing, particularly when used as a tool with a specific purpose. Fire was also a negative wellbeing converter, principally as a hazard unrelated to the original purpose, when it became uncontrollable. However, most respondents prioritised the use of fire as a tool, and considered these hazards as sometimes-unavoidable risks related to activities necessary to achieving broader wellbeing goals.

6.3 Fire causes and consequences: synergies and trade-offs

Livelihood uses of fire, the ecosystem services enhanced by fire use, and associated hazards identified here are similar to those identified in other studies (e.g. Kikula, 1986; Eriksen, 2007; Shaffer, 2010; Ribeiro et al., 2019). In Kilwa, the fire regime resulting from largely intentional human ignitions is characterised by frequent, late-season burning (chapter 4). In general, late dry season fires are likely to be more intense than early dry season fires (though this effect may be weak at landscape scales; Archibald et al., 2010) and experimental evidence suggests that frequent, intense fires are more likely to result in tree mortality (Trapnell, 1959; Ryan & Williams, 2011). Yet, the current fire regime which is dominated by late dry season burning did not cause degradation of large trees in Kilwa over nine years (chapter 3).

Fire reduced growth of large stems, but growth and recruitment rates remained high enough to offset biomass losses to mortality. While this evidence is insufficient to address questions about the ecological impacts of fire on more vulnerable tree seedlings, saplings and herbaceous vegetation (chapter 3; Frost, 1996), I show that important ecosystem services provided by large trees – including timber provision, carbon storage, and biodiversity – were stable over 9 years.

The fire regime also provided local people with many benefits. The most common fire causes were intentional (chapter 4) and related to important wellbeing goals including the capability to pursue livelihoods successfully and the capability to feel safe and secure (chapter 5). However, there were trade-offs related to wellbeing goals resulting from fire use (Table 5.2). Fire caused damage to property, natural resources, and posed a safety risk to people. Some were more vulnerable to losses from fire – including those (often women) who collect and sell grasses.

In general, controlled fires were associated with many benefits and few risks (if they remained controlled), while uncontrollable fires were associated with specific benefits for the fire user, as well as risks for others (chapters 4 & 5). For example, fires used by hunters and livestock keepers were intentionally large, uncontrollable and therefore potentially hazardous. However, these fires generated benefits for those who set them and, to a lesser extent, those who bought and ate meat and milk.

Fire users were, of course, aware of these risks and chose to set fires anyway. Charcoal makers told us how smoke was bad for their health, but they made charcoal because it gave them a second source of income alongside farming. Uncontrollable fires in general were a threat to safety, but there was an immediate safety risk associated with walking through unburned long grasses which harbour dangerous wildlife – so people set fire in them. These findings show that people in the study site often prioritised the use of fire as a tool and the benefits gained from this, despite associated risks, as has been reported in Madagascar (Kull, 2016).

Fire management in Kilwa involved individuals and small groups deriving benefits from fire use while taking precautions to manage the risks, such as burning in cool and wet conditions, working with neighbours to burn fields, or using prescribed burning to protect important places from fire (chapter 4). Uncontrollable late season fires were also a desired part of the fire regime and, while these fires were set far from the village centre, they were inherently associated with more risk than small controlled fires. Additionally – any fire could accidentally go out of control. There were no formal mechanisms for compensation, though occasionally some was given informally, and this created some hardships (chapter 5). However, in general, risks associated with fire used for important livelihood activities were considered unavoidable and forgivable.

These findings show that from many perspectives, the fire regime as currently managed by local people in Kilwa is successful. Fires are usually set for important benefits (chapter 4) and have positive impacts on wellbeing (chapter 5) without causing the loss of large trees (chapter 3). Yet, despite precautions taken, there remains a risk of hazardous and harmful consequences of fire (chapter 5).

6.4 Does fire cause degradation?

In the Introduction I discussed how degradation narratives have shaped fire management and policy since colonial rule in many parts of Africa (section 1.3). Several of the fire causes identified in this thesis, including some of the most common and risky causes such as field preparation, clearing a path and livestock keeping (chapter 4) have been characterised as 'degrading' since this time (section 1.3). It is now well established that fires, mainly ignited and managed by people, enable stable savanna ecosystems (Bond & Keeley, 2005; Staver et al., 2011). Fire therefore often delivers services provided to ecosystems by people (Comberti et al. 2015). However, with growing rural populations and changes to land management in southern Africa, researchers now question whether there is "too much, too little, or the wrong type of fire" (Shlisky et al., 2009). Fire-based livelihood activities continue to be identified as causes of degradation by experts with environmental concerns, and indeed have been blamed in part for fire regimes themselves being 'degraded' (though fire mismanagement by, for example colonial authorities, is also recognised; section 6.1).

In the study communities in Kilwa, people also reported that repeated fire degrades the land or turns it to 'desert' (chapter 4). This conviction apparently came not from experience or knowledge passed down within families or communities, but rather from government employees such as school teachers, or from environmental NGOs. Some reported that the long-term negative impacts of fire were simply well-known, though very few claimed to have witnessed this effect. While I didn't study this issue in great depth, this is tentative evidence, corroborating the findings of Brockington (2006) and Gross-Camp (2017), that environmental narratives in Tanzania result in local people believing that their traditional land management activities are old-fashioned and harmful. People are taught that modern approaches to land management which prioritise conservation, would be preferable.

This was reiterated by respondents reporting that they would be happy for alternatives to fire for activities such as farming, partly so that they no would no longer be "destroying the area" with fire (chapter 5). This narrative results in confused local perspectives of fire (or at least, the perspectives that were shared with us, the researchers). Respondents observed that fire had always been a normal part of life, and that village land recovered from fire (chapter 4). They had been taught by their parents and grandparents how to manage fire well, reducing hazards (chapter 4). For some activities, like clearing a safe path through the savanna (burning away the grass that snakes may otherwise hide in) there aren't viable alternatives to fire (chapter 5).

It is striking that when respondents reported that repeated fires turned the land to desert or caused water sources to dry up, the focus of concern was trees (people reported that if fires destroyed all the trees that shade water sources, then all the water would evaporate in the heat). This reflects the major focus of degradation narratives since colonial times – when ecological theory held that savannas represented stunted succession of vegetation to 'climax' forest ecosystems. Timber was then, and still is, a valuable economic resource. Trees and forests are still at the centre of narratives about degradation and fire, reinforced by, for example, the UNFCCC, the CBD, as well as the governments and organisations that are influenced by these treaties and their outputs (section 1.3).

In chapter 3 I demonstrated that, while fire limits growth of large trees, it does not drive their degradation (by the UNFCCC definition, where degradation is equated to forest loss). With ≥40 cm diameter individuals containing around one third of AGC in Kilwa (McNicol et al., 2018) and with trees dictating other aspects of woodland functioning and diversity in miombo woodlands (Moura et al., 2017), this is an indicator that both biodiversity and carbon storage were maintained under the fire regime. It is of course important to look beyond the impacts of fire on large trees, from both a conservation and social perspective. Unfortunately, ecological study of other taxa was beyond the scope of this study.

The social research in this thesis demonstrates that fire supports several ecosystem services and enhances the usefulness of land and resources in Kilwa. Fire is used to prepare agricultural land and fresh grazing, clear a safe path, make for easier hunting and honey collecting, make charcoal, to protect important areas from later fires (chapter 4). Aside from enabling people to make money, grow food and have enough to live, the livelihood activities that fire enables contributes to a broader sense of control people have over their own lives, and freedoms to achieve what they want to achieve (chapter 5). Fire is a means to several wellbeing ends, including feeling safe from wild animals, and from later fire. However, some ecosystem services are degraded by the presence of fire; for example when thatching grasses burn away. Further, uncontrollable fire – while bringing some of these benefits – is a hazard which can generate economic losses, physical harm, and a sense of fear.

In this thesis I have therefore provided evidence that, from a conservation perspective, the current fire regime does not drive degradation in Kilwa (chapter 3). The perspectives of local people are more complex. Many repeat the environmentalist narrative that in the long-term, fire degrades the land. However, people continue to use fire for land management, resulting in a largely intentional fire regime which contributes to livelihoods and broader wellbeing goals (chapters 4 & 5). The main reasons people use fire is that it increases usefulness of the land. By the measure of its continued use and reported benefits therefore, fire is not causing degradation in Kilwa. However, while fire enhances the usefulness of the land for most in Kilwa, its harmful and hazardous impacts are significant, and ways of managing fire to reduce these impacts should not be overlooked.

6.5 Integrating social and environmental goals for sustainable fire management

Where it has been contrary to or undermined human uses of fire, formal fire management has failed (e.g. Trollope & Trollope, 2004; Kagosi et al., 2020; Kilawe et al., 2021). The findings here, echoed elsewhere (e.g. Hough, 1993; Kull, 2004; Shaffer, 2010), that people in inhabited landscapes burn to meet individual, livelihood goals (chapter 4), and that fire use impacts local wellbeing (chapter 5) supports calls for Integrated Fire Management (IFM) which engages with local communities. The knowledge and opinions of individuals involved in different livelihood activities (both those that use fire and those who are impacted by it such as grass collectors) are necessary to devise management strategies which do not infringe upon or undermine these goals.

This kind of IFM, which truly engaged and deliberated with local communities, was found to be successful (at least in the short term) in Brazil: whereby community engagement increased over time, formal agreements were made between communities and protected area managers, and uncontrolled late dry season fires decreased (which was the main aim of the management) enabling a reduction in firefighting costs (Schmidt et al., 2018). Similarly, across multiple case studies of community-based fire management around the world, a sense of ownership has been identified as key to sustainable fire management in which local people are motivated to be actively involved (Ganz & Moore, 2002). Relatedly, the ability to control and access resources has been found to motivate people in Kilwa and elsewhere in Tanzania to participate in community forestry, even when the financial benefits are limited (Gross-Camp, 2017).

This approach to fire management contrasts with merely granting legal rights to manage fire, which as reported by Ganz & Moore (2002) does not automatically create a sense of ownership and which, as I have shown in this study (chapter 4), may be poorly understood by local communities anyway. It also contrasts with 'integrated' fire management where local communities are merely trained in fire management techniques (Eloy, 2019; Pooley, 2021). Rather, local people's views and expertise should be integrated into all aspects of management plans and processes, with real ownership and influence over fire management outcomes. My finding in chapter 5 that freedom and choice is crucial to wellbeing, and that livelihood uses of fire contribute to people's freedoms and control over their own lives, provides yet more support for this kind of IFM.

In Kilwa, I find no evidence that fire causes environmental degradation (section 6.4) though this is not to say the fire management may be desirable to achieve some specific environmental goals, such as the conservation of certain species, and to reduce fire hazards. People in Kilwa are aware of environmental implications of fire use and feel a responsibility to care for the environment for themselves and for future generations (chapter 5; Gross-Camp, 2017). Based on the findings of this research and my experiences in the study villages, I see no reason why well-planned fire management with clearly communicated environmental goals would not be welcomed here. Indeed, several times during the course of data collection, people asked to be taught more about the best ways to manage fire for environmental benefits.

However, any fire management could conflict with livelihood uses of fire. This could result in two potentially negative impacts: harming the livelihoods and wellbeing of local people, or, the more likely alternative is that the fire management would simply fail. People would continue to burn but be more secretive about it. I have demonstrated in this thesis that people often prioritise the use of fire as a tool, despite associated risks or perceived negative impacts on the environment (chapters 4 and 5); a similar finding has been reported in Madagascar (Kull, 2016). Even if people were paid to manage fires in order to achieve some environmental goals, they would not and should not stop using fire for livelihood activities like farming and livestock keeping. IFM which truly integrates the interests of local people by embedding existing livelihood activities and fire uses into the strategy is more likely to deliver environmental and social benefits in Kilwa.

Local residents in Kilwa manage fire in a way that is adaptive and responsive to environmental conditions (chapter 4). This contradicts the perception reported by Ylhäisi (2003) that as local people have moved from their traditional ranges, they no longer know how to manage their environment. This kind of ecological knowledge can clearly be of immense value to fire managers with a variety of social and environmental goals (Mistry et al., 2016). The inherent complexity, uncertainty and change of socio-ecological systems requires governance which is similarly adaptive (Folke et al., 2005; Schmidt et al., 2018). The environmental goals of IFM are more likely to be achieved if local expert knowledge is utilised.

So what could IFM look like in Kilwa? First, strong, clearly communicated national policies are necessary for successful local governance. A review by the Food and Agricultural Administration found that fire was not well-covered by existing policies and acts in Tanzania, that many local governments had no by-laws, and where there were relevant by-laws they were poorly implemented (FAO-Finland Forestry Programme – Tanzania, 2013). This finding was upheld by my own research into current fire policy in Tanzania, and also respondents' (including some Village Executive Officers who are government employees) confusion about what the laws about fire are (chapter 4). No respondent accurately told me what the regulations about fire were in Tanzania.

Based on the findings in this thesis, I agree with the findings of the FAO-Finland Forestry Programme report (2013) that a dedicated fire policy and a clear institutional framework for fire management would help to combat this and consolidate the fire rules currently scattered in other policies. But this fire policy must allow flexible, adaptive, and contextually-appropriate fire management (Schmidt et al., 2018). Further, it must be relevant to the lives and livelihoods of local communities, supporting local economic activities and wellbeing. The rules about fire in Tanzania's 2002 Forest Act, which allows people to burn their own land but requires people to seek permission if burning elsewhere, currently falls short of this. While this policy recognises that local people use fire in controlled ways on their own land, it does not acknowledge the need to use uncontrollable fires, such as for livestock keeping, hunting and to clear a path, which undermines its applicability to peoples' real circumstances.

The problems with fire in Kilwa, as identified in this thesis, are mostly social and related to hazardous impacts, particularly when fires are uncontrollable. In different fire management approaches… "achieving control (be it of fuels, ignitions, or fire spread) is the common denominator" (Castro Rego et al., 2021). Achieving control, too, is likely the common denominator to enable ecosystem services to continue to be enhanced by fire in Kilwa, and achieve wellbeing goals while limiting fire hazards (chapter 5). This may involve, for example, reducing fires which accidentally go out of control (including late dry season fires) by setting fires in cool, wet conditions: a method already used by many residents.

However, as there are some contradictory goals for fire use, achieving control in practice is complex. Some uses of fire such as for hunting – while controlled in the sense that people choose the location of burning – need to be uncontrollable to some extent to be useful. Therefore a combination of factors is more likely to be necessary for implementing IFM and reducing fire hazards in Kilwa. This could include improving fire fighting resources and preventative measures such as improving control over some burning (for example by clearing bigger fire breaks) and using non-flammable materials for buildings.

Some researchers working in African countries have reported that local fire management results in patch mosaic burning. This kind of management, while meeting the social aims of the fire users, has hypothesised (though, weakly evidenced) benefits for biodiversity (Laris, 2002; Butz, 2009). In contrast with these findings, fire management in Kilwa did not result in patch mosaic burning (chapter 4). Only a relatively small land area burned during the early dry season, with the largest area burning during the late dry season – both because people chose to set fires at this time, and because conditions encouraged fire spread. Sometimes, people also choose to set fires in hot and windy conditions because these conditions encouraged fire spread.

In places like Kilwa where there are lots of late dry season fires academics who perceive this to be problematic increasingly recommend prescribed early dry season burning, sometimes as part of patch mosaic burning, as a fire management strategy (Chidumayo, 1997; Nieman et al., 2021; Ribeiro et al., 2021). Most of the evidence in favour of prescribed burning comes from a handful of ecological studies in which the distinction between early and late fire is simplistic (Laris et al., 2016) while the social benefits of prescribed burning are theorised rather than studied. Transplanting these learnings to fire management without taking into account local environmental conditions and social context is wildly insufficient.

In Kilwa, early dry season burning may reduce the risk of some of the harmful effects of fire (by reducing fuel loads for late dry season fire and subsequently reducing their potential spread and severity) (Nieman et al., 2021). Indeed, many people burn fire breaks around their homes and farms in the early dry season for this reason, though others set protective fires throughout the dry season (chapter 4). Early burning could therefore be an important part of IFM in Kilwa, particularly in order to reduce fire hazards. But it is not a silver bullet. Late fires are needed too, for example to generate fresh grazing and to clear agricultural land (chapters 4 & 5). More early dry season fires could increase some types of fire risk because they are more likely to burn crops that have not yet been harvested (harvest time for most crops is during the late wet season or early dry season).

The received wisdom says that early burning can deliver ecological benefits – allowing fires with reduced intensity, in order to limit late fires which cause degradation – while meeting people's needs. But this is an oversimplification, in Kilwa and elsewhere. As Mistry et al. (2016) write:

> "…the institutionalization of Indigenous fire management, and its scientific and technocratic discourse strongly privileges one particular aspect of Indigenous fire management: early dry-season burning to protect against late dry-season burning… This fails to recognize that Indigenous fire management is characterized by regular and sometimes opportunistic burning throughout the dry season linked to various social, ecological and spiritual purposes…"

Careful planning of the timing and locations of burning by local communities would therefore be needed to ensure that (early) burning can deliver benefits without increasing risk. The impacts of any interventions like this would need to be monitored.

The prescribed burning around Kilwa's community forests forms part of the wider community forest management led by MCDI. It involves training, guidance and planning from MCDI (who, according to respondents in villages and MCDI employees) often direct burning based on satellite images of fires and vegetation). The respondents who have been involved say that prescribed burning is successful at excluding late fires, and are proud to have contributed to protecting their community forest. Some have also been involved in planning burns, and some villages continued early burning without MCDI's input in years following initial trainings. This may therefore be a small-scale example of successful IFM. The burning is contained to the community forests only – respondents who weren't involved often did not know that there was any fire management – and no one reported that it infringed on their land management or use of fire outside of the forests. Of course, larger-scale fire management would be more likely to affect livelihood and other uses of fire, and would require engagement with all parts of the local communities.

The ways people in the study villages used fire and perceived its impacts were influenced by personal experiences, education from parents and grandparents, as well as formal education from government employees (*Bwana shamba*, *Bibi shamba* and school teachers) and NGOs. In general, people were taught by government employees and NGOs the environmentalist narrative that fire is degrading (as discussed in section 6.4). The data here were insufficient to explore the possibility that such narratives may encourage secrecy in burning, as has been found in other African communities (Kull, 1999; Laris, 2002; Butz, 2009).

However, surely these narratives undermine open discussions about the costs and benefits of fire, which are required for IFM to be successful. We found that respondents were often very reluctant to discuss fire uses, especially in illicit activities such as hunting, and share experiences of fires they set becoming uncontrollable. I suspect that the narrative that fire is harmful to the environment (which appears to be deeply ingrained in the study communities, and which respondents may have thought represented the views of us the researchers) were part of what stifled these conversations. There may be much work to be done to overcome these simplistic narratives and encourage more nuanced conversations about fire causes and impacts, to enable collaborative and productive planning of IFM in communities throughout Africa.

6.6 Concluding remarks

The findings in this thesis point to the complexities and contradictions associated with fire uses and impacts in Kilwa. Fire is a hazard to local people, but its use is necessary to many livelihood activities and achieving wellbeing goals. The findings here also suggest that fire management – controlled mainly informally and by individuals – is in many ways successful: the current fire regime is useful to people, and is not a threat to many of the important ecosystem services provided by trees. I show that personal controls and freedoms, related to how people live their lives and manage their environment, are important to local wellbeing. This echoes work in other ecosystems and studies of other types of land use and management. Therefore, while this thesis outlines specific, context-dependent, case study findings, it also provides evidence for general approaches. Namely, it supports calls for meaningful engagement with rural communities for successful fire management: which can both be improved by local knowledge and provide benefits to global and local populations.

6.7 References

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Appendices

Appendix 1: Example map from participatory mapping exercise in Ngea

Appendix 2: Interview prompts for wellbeing focus group discussions and participatory mapping

In the FGDs we use the terms *ustawi* (welfare) and *hali ya maisha* (conditions of life) to discuss wellbeing.	
Part 1	**Discussion about what wellbeing means in the community. Give definition of "Wellbeing is concerned with the factors contributing to living a good and satisfying life"**
1.01	What impacts wellbeing in your community, in both beneficial and harmful ways? (people might be more likely to focus on benefits – ensure to prompt discussion of both benefits and harms until respondents are happy that their list is complete)
1.02	How would you describe someone who has high wellbeing in your village?
1.03	How about someone who has low wellbeing?
1.04	If two people have the same wealth, can they have different wellbeings?
1.05	Are any aspects of wellbeing linked to material goods? Your body? Social relations? Security – now and in future? Freedom and choice?
Section 2	**Please draw a map of your village, and its surrounding land – any land people go to – and please mark out places that are important for wellbeing. Please show us places which both benefit and harm wellbeing (people might be more likely to focus on benefits – ensure to prompt discussion of both benefits and harms until respondents are happy that their map is complete). If it isn't clear, ask what type of land this is, who uses this land?**
2.01	(Focusing on ecosystem services and disservices) Why have you marked this place as important for your wellbeing?
2.03	Could you tell us some benefits and harms in nature? (people might be more likely to focus on benefits – ensure to prompt discussion of both benefits and harms until respondents are happy that their list is complete)
2.04	Do you think that these benefits and harms impact your wellbeing? How?
Section 3	**Fire**
3.01	Please mark on the map where there have been fires in your village in the past 12 months. Please distinguish "WF" wildfire and "CF" controlled fire, and give the reasons controlled fires were set.
3.02	Have any of these fires gone out of control in the past 12 months: Clearing farms, livestock keeper fires, hunter fires, fires for protection from other fires, or animals, fires set while collecting in the forest, household fires, preparing medicines, accidental, fires for spiritual purposes, natural fires, by the village?
3.03	Has fire impacted any of these places that are important for your wellbeing? How? What about other aspects of your wellbeing? What about other benefits and harms in nature?

3.04	Are controlled fires and wildfires different now than in the past? If so, how and why? Has this impacted your wellbeing?
3.05	Do you think that changes to the way fire is used by people could impact your wellbeing in the future? How? (in intervention villages – what about early burning?)
3.06	Do you think that if the frequency of wildfires changed – increased or reduced – this would impact your wellbeing?
3.07	Do you think that fire influences your wellbeing? How?