Drivers of tropical deforestation and forest regeneration in Tanzania

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Declaration of Authorship

The candidate confirms that the work submitted is her own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Chapter 3 is the publication Doggart, N., Morgan-Brown, T., Lyimo, E., Mbilinyi, B., Meshack, C.K., Sallu, S.M., Spracklen, D.V., 2020. *Agriculture is the main driver of deforestation in Tanzania*. Environmental Research Letters 15, 034028.

The research was conceptualised and planned by the candidate with input from T Morgan-Brown, B Mbilinyi and E Lyimo. The paper was written by the candidate with advice from supervisors (S Sallu and DV Spracklen) and additional comments from co-authors (B Mbilinyi, CK Meshack and T Morgan-Brown). The deforestation analysis was carried out by T Morgan-Brown. The accuracy assessment for the deforestation analysis was carried out by the candidate and T Morgan-Brown. Other data analysis was carried out by the candidate using a dataset collected by E Lyimo and L Santos.

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Abstract

Forest cover change affects ecosystem services including climate and biodiversity. Global efforts to reduce deforestation, and restore forest cover, depend on understanding the rates and drivers of forest cover change. Knowledge gaps are greatest around rates and drivers of forest regeneration, and drivers of deforestation in Africa. Determinants of the rate of biomass and species accumulation in regenerating forests, are also poorly understood. Although deforestation rates have been well-studied, published rates still vary significantly, particularly in African woodlands.

This thesis investigates rates and drivers of deforestation and natural forest regeneration, with a focus on Tanzania, a country with the fifth highest net deforestation, globally. Using innovative, inter-disciplinary methods, the study presents new empirical evidence on rates and drivers of forest cover change. Linking this to policy, the thesis provides new insights on the challenges of using an energy-transition policy, to reduce deforestation.

New datasets show that deforestation exceeds regeneration by >0.5 Mha y^{-1}. Tanzania's national gross mean annual deforestation rate is calculated at 1.42% or 0.562 Mha y^{-1} (0.46 – 0.66 Mha y^{-1}) (2010 – 2017). For village land, a land class that excludes protected areas, the gross mean annual deforestation rate is higher, at 1.9% or 0.608 Mha y^{-1} (0.46 – 0.78 Mha y^{-1}) for the more recent period of 2011 – 2021. The gross mean annual regeneration rate on village land is far lower at 0.0132 Mha y^{-1} (0.004 – 0.03 Mha y^{-1}) (1987 – 2021).

New evidence is presented that agriculture causes most deforestation (81% of deforestation events), compared with only 12% attributable to charcoal. In regenerating woodlands, agricultural fallows were the most frequent regeneration driver, while biomass and species accumulation were most affected by regeneration time and precipitation.

While forest and energy policies have sought to curb deforestation through an energy transition away from woodfuel, the policies have been ineffective for two reasons. Firstly, they do not address the main deforestation driver,

agriculture. Secondly, they have had limited impact on charcoal consumption, with 88% of Dar es Salaam households still using charcoal in 2018.

Reducing deforestation and amplifying natural regeneration both require closer inter-sectoral coordination. With most deforestation occurring on village-owned land in Tanzania, there is an urgent need for more effective strategies to enable communities to retain forest products and services critical to livelihoods.

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List of Abbreviations and Acronyms

AGB	Above-Ground Biomass
ALOS	Advanced Land Observing Satellite
a.s.l.	Above sea level
BA	Bushland
BT	Thicket
C	Carbon
CL	Lowland forest
COVID-19	Coronavirus Disease-2019
CP	Conference of Parties (to the UNFCCC)
DECAF	Deforestation-Climate-Atmospheric composition-Fire interactions and Feedbacks
DN	Digital Number
EWURA	Energy and Water Utilities Regulatory Authority, Tanzania
FAO	Food and Agriculture Organisation
FC	Forest Cover
FREL	Forest Reference Emission Level
FSSP	Field Survey Sample Plot
FTM	Forest Transition Model
GEE	Google Earth Engine
GFL	Gross Forest Loss
GFRA	Global Forest Resources Assessment
GFW	Global Forest Watch
GHG	Greenhouse Gases
GPS	Geographical Positioning System
ha	Hectare
HV	Horizontal-transmitting Vertical-receiving

IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram = 1,000 grams
kWh	Kilowatt-hour
LGA	Local Government Authority
LPG	Liquefied Petroleum Gas
m	Metre
Max	Maximum
Mg	Megagram = 1,000,000 grams or 1 tonne
Mha	Million hectares
Min	Minimum
MJ	Megajoule = 1,000,000 Joules
MNRT	Ministry of Natural Resources and Tourism, Tanzania
MW	Miombo Woodland
N/A	Not available or Not applicable
ODK	Open Data Kit
PhD	Doctor of Philosophy
PJ	Petajoule = 1,000,000,000,000,000
REDD+	Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks
RS	Remote Sensing
SDG	Sustainable Development Goal
SI	Structured Interview
Tg	Teragram
TFCG	Tanzania Forest Conservation Group
TFS	Tanzania Forest Services Agency
TRA	Tanzania Revenue Authority

TZA	Tanzania
TZS	Tanzania Shilling
UNFCCC	United Nations Framework Convention on Climate Change
URT	United Republic of Tanzania
US$	United States Dollar
VAT	Value Added Tax
y	year

Chapter 1 Introduction

This chapter begins by locating the thesis in the context of current global issues. Key terms are then defined. This is followed by a review of current knowledge and knowledge gaps on deforestation and regeneration drivers and related policy, at a global or pan-tropical scale. In Section 1.2, the study area, Tanzania, is introduced. This is followed by a more granular review of the literature on the key research topics, focusing on Tanzania and adjacent countries. Building on the identification of what is, and is not, known about forest cover change rates and drivers (Sections 1.1 and 1.2), the research aim and objectives are presented in Section 1.3. The thesis structure is then described. The chapter ends with an explanation of the motivation for the research (Section 1.4).

1.1 Context

Despite humanity's profound understanding of the existential threats triggered by tropical deforestation, our species continues to convert forest biomass into climate-disrupting gases, extinguish tropical forest biodiversity and interrupt the processes that provide us with life-sustaining fresh water (Ellison et al., 2017; Lewis and Maslin, 2018).

Documenting the rate and direction of net forest cover change can help to focus people's attention on the issue of tropical deforestation and can motivate action to avert further loss. Data on the relative contribution of different deforestation drivers empowers policy-makers and forest management practitioners to prioritise deforestation-reduction action and investment to counter the most destructive activities. Similarly, an understanding of the actions that drive natural forest regeneration, can be used to enhance forest restoration initiatives (Gann et al., 2019). With a focus on Tanzania, this thesis examines rates and drivers of tropical forest loss and gain, and examines how mis-identification of drivers of deforestation can undermine policy impact.

By increasing knowledge of forest cover change dynamics, the thesis has relevance to various international agreements and processes including the

Paris Agreement (UNFCCC 2015, 1/CP.21 Article 5), the Sustainable Development Goals (SDG), particularly SDG 13 Climate Action and SDG 15 Life on Land, and the Bonn Challenge target to restore 350 million hectares (Mha) of deforested and degraded landscapes, by 2030.

1.1.1 Definitions

The thesis applies the following definitions:

Terms for forest and forest cover change

Forest: the thesis uses Tanzania's official definition of forest as '*an area of ≥0.5 ha with ≥10% canopy cover of trees ≥3 m in height*' (United Republic of Tanzania, 2017). This definition is derived from land cover, rather than land's legal status or use. A definition based on land cover is more relevant to the remote sensing components of the study. The definition also aligns the research with Tanzania's national statements on forest cover. However, it is recognised that there are many ways to define 'forest' (Lund, 1999). It is also acknowledged that some of Tanzania's open woodland, classified as forest using the Tanzanian official definition, would be considered tropical savanna using other classification systems, given its fire-dependence and presence of C4 grasses (Ratnam et al., 2011).

Deforestation: while deforestation can be defined with reference to changes in the legal status of land and / or its land cover and / or its land use (Lund, 2015, 1999), in this thesis, deforestation is again defined on the basis of land cover as '*the conversion of forest land to non-forest land*' (IPCC, 2000).

Natural forest regeneration: the conversion of non-forest land to forest land through natural succession in an area deforested in the last 50 years. This is based on the definition used in the Food and Agriculture Organisation (FAO) Forest Resources Assessment 2020 '*forest predominantly composed of trees established through natural regeneration*,' distinct from their definition of reforestation as the '*re-establishment of forest through planting and/or deliberate seeding on land classified as forest*'.

Forest degradation: 'a direct human-induced loss of forest values (particularly carbon), likely to be characterised by a reduction of tree crown cover' (Karjalainen et al., 2003).

Biomass: Unless otherwise specified, biomass refers to above ground biomass including alive and standing dead trees. For Chapter 4, this also includes biomass cleared in the last 4 years, calculated from stumps.

Terms for drivers of forest cover change

Direct drivers of deforestation are the local-level human activities that directly result in a loss of forest cover (based on Geist and Lambin 2002 and Hosonuma et al. 2012). Direct drivers are the focus for this thesis.

Indirect drivers of deforestation include the multi-scale interactions between economic, policy, technological, cultural and demographic forces that result in the direct drivers (based on Geist and Lambin 2002; Meyfroidt et al. 2022).

Drivers of natural forest regeneration are defined as changes in land use that result in a change in land cover from non-forest to forest through natural regeneration. This includes the cessation of an activity, such as crop cultivation, previously preventing forest growth. This definition differs from other studies which have focused on variables affecting forest growth rates or forest land expansion and is discussed further in Sections 1.1.4 and 1.1.5.

1.1.2 Tropical forest cover change

Understanding of tropical forest cover change and related carbon fluxes has increased over the last 20 years. Knowledge gaps remain, particularly for Africa. The Forest Transition Model provides a useful lens through which to view deforestation trends.

Tropical forests are important for global climate (Baccini et al., 2012; IPCC, 2022a), livelihoods (IPCC, 2022b) and biodiversity (Brondízio et al., 2019). There has been a net loss of tropical forests over the last four decades, balancing canopy cover loss of 92.7 Mha against canopy cover gain of 83.7 Mha between 1982 – 2016 (Song et al., 2018) accelerating to 110.6 Mha total loss in tree cover extent against 24.7 Mha gain in tree cover extent, between 2000 – 2012 (Hansen et al., 2013 Table S2).

As a result, tropical forests are a net source of ~425.2 ± 92.0 Tg C y^{-1} into the atmosphere, balancing losses from deforestation and forest degradation of 861.7 ± 80.2 Tg C y^{-1} against gains from forest growth of 436 ± 31.0 Tg C y^{-1}

(2003-2014) (Baccini et al., 2017), equivalent to approximately 2.67% of global net anthropogenic greenhouse gas (GHG) emissions in 2019 (15,930 ± 1,782 Tg C y^{-1} (IPCC, 2022a)[1]). While the estimates of gross fluxes of atmospheric carbon to / from tropical forests vary significantly, there is broad consensus that tropical forests are a net source of atmospheric carbon (Achard et al., 2014; Lewis et al., 2015; Pan et al., 2011). Forest cover change and carbon fluxes in low biomass and secondary forests, in Africa, are repeatedly identified as areas of uncertainty (Requena Suarez et al., 2019; Rozendaal et al., 2022).

Many countries and regions have followed a trajectory of accelerating then decelerating forest cover loss, until reaching a forest cover nadir or base level. This is followed by an increase in tree cover, often dominated by plantations (Lewis et al. 2019). Based on empirical evidence, the Forest Transition Model (FTM) describes this typical trajectory of forest cover change (Figure 1) (Mather, 1992; Mather and Needle, 1998). In the pre-transition phase, forest cover is high while the net deforestation rate is low. In the early transition phase, deforestation accelerates before decelerating in the late transition phase. In the post-transition phase, tree cover increases but remains low. While the thresholds between these phases vary between countries and over time, the overall pattern is broadly similar (Angelsen and Rudel, 2013). Figure 1 shows the inter-phase thresholds used by Pendrill et al. (2019). Most deforestation occurs in the Early Transition phase.

With growing awareness of the value of natural forests, measures can be taken to maximise the area of natural forest that persists through to the post-transition phase (Rudel et al. 2020). With investment and policy support, countries can strive to attain a high natural forest base level. This requires an understanding of how far along the model a country has progressed and deliberate action to reverse net forest loss (Furumo and Lambin, 2021). Data on the net deforestation rate and the main deforestation drivers are needed

[1] This applies a 0.27 (11/44) conversion factor to the values in B1.1 SPM-4 of the Summary for Policy Makers in IPCC, 2022, where it is stated that '*Global net anthropogenic GHG emissions were 59 ± 6.6 GtCO2-eq in 2019*'.

for nations to slow the rate of net forest loss and maximise the base level forest area, effectively flattening and shifting the forest transition curve upwards. This principle has guided climate change mitigation efforts under the umbrella of REDD+ (Reducing Emissions from Deforestation and forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks) (Angelsen and Rudel, 2013).

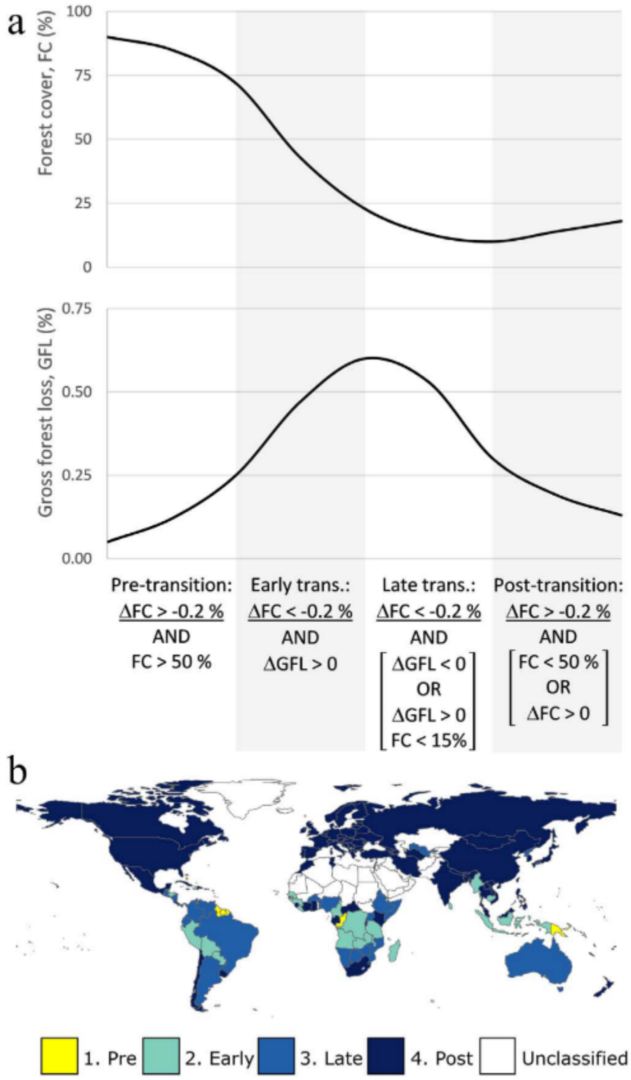

Figure 1 the Forest Transition Model

(a) Schematic representation of the forest transition, with the decision algorithm used to classify countries into four stages: pre-, early-, late-, and post-transition. FC = forest cover; ΔFC = net forest cover change; ΔGFL = trend in gross forest loss (deforestation). (b) Map showing countries classified into forest transition stages. Countries marked as 'unclassified' are primarily those with a forest cover below 5%. Figure reproduced from Pendrill et al. 2019.

While the forest transition model provides a useful lens to contextualise forest cover change over time, it has been critiqued as a colonialist worldview that uses the land cover change and economic growth trajectories of Europe and America as a deterministic benchmark for the rest of the world. It is argued that the model ignores inequalities and '*invisibilizes the role of smallholder farmers and Indigenous communities in combating forest destruction and the ravages of capitalism*' (Liebman and Gagliano, 2021). This highlights the importance of a more nuanced, contextual and evidence-based understanding of forest transitions, that recognises the role of marginalised groups including subsistence farmers and local communities in enhancing forest carbon stocks (Rudel et al. 2021). While mindful of these risks, the forest transition model is nonetheless valuable in contextualising countries' forest cover change status. It is used throughout the thesis to draw connections between Tanzania's specific situation and broader global trends. With Tanzania as a case study the thesis looks at how countries can assess their position on the forest transition model; identify the activities and actors driving their national transition and use that information to inform policy.

1.1.3 Drivers of tropical deforestation

At a pan-tropical scale, research on tropical deforestation provides an increasingly elaborate picture of direct and indirect deforestation drivers.

Reducing deforestation has been a key goal in international climate and biodiversity agreements including the Paris Agreement (UNFCCC, 2015) and the Convention on Biological Diversity (United Nations, 1992). This has focused attention on the direct and indirect drivers of deforestation, with requests to the Parties of the United Nations Framework Convention on Climate Change (UNFCCC) to identify and address deforestation drivers (UNFCCC 2/CP.13, 4/CP.15, 1/CP.16, 15/CP.19).

Globally, agriculture is the main direct driver of tropical deforestation (Curtis et al. 2018; Geist and Lambin 2002; Gibbs et al. 2010) with estimates of its contribution ranging from 82% – 99% of tropical deforestation (De Sy et al. 2019; Hosonuma et al. 2012; Pendrill et al. 2022). Other direct drivers of deforestation include infrastructure, settlement, and industry including mining. Activities that result in temporary forest clearance but do not result in a change in land use, such as charcoal production, fuelwood collection, timber harvesting and fire, are usually considered drivers of forest degradation but can result in temporary forest clearance (Hosonuma et al., 2012).

‘Agriculture’ is a very broad class of deforestation driver. Over the last two decades, a more nuanced understanding of the types of agriculture that drive deforestation, at a global scale, has emerged. This has involved different classifications of ‘agriculture’. Some studies simply distinguish between commercial and subsistence agriculture, where the former includes production on medium to large scales for international and domestic markets while the latter includes permanent or shifting cultivation by small-scale farmers, primarily for subsistence. For example, Hosonuma et al. (2012) found that commercial agriculture was the driver of more deforestation (40%) than small-scale agriculture (33%) across the tropics, while De Sy et al. (2019) expanded this classification to include a separate class of ‘pasture’, finding that 52% of agriculture-driven tropical deforestation areas were converted to land used predominantly for grazing, with 88% of that area in Latin America. In a pan-tropical sample-based assessment of deforestation drivers (2008 – 2019), subsistence agriculture was found to cause approximately 50% of deforestation, significantly exceeding commercial agriculture including forestry (~20%) and pasture (~16%) (from datasets published by Laso Bayas et al., 2022).

Other studies have disaggregated agriculture-driven global deforestation by product, finding that beef cattle, palm oil and soya bean cause 40 – 45%, 7 – 11% and 7 – 8 % of deforestation, respectively (Goldman et al., 2020; Pendrill et al., 2019). Such studies have advanced knowledge at a global or pan-tropical scale. They have also highlighted regional differences, with Africa remaining an outlier in terms of the high contribution of small-scale crop farming (61.1%), compared with Latin America (3.5%) and Asia (35%) (De Sy et al., 2019).

Inevitably, many studies have focused on a few countries, particularly the top-three net deforestation countries: Brazil, Indonesia and the Democratic Republic of Congo (Austin et al., 2019; Busch and Ferretti-Gallon, 2017; Tyukavina et al., 2018). For many countries there remain significant gaps in our understanding of the relative contribution of deforestation drivers, particularly for African countries (Pendrill et al., 2022). Other key gaps include the interaction between co-occurring drivers of deforestation and degradation, and, for agriculture-driven deforestation, the contribution of agricultural products beyond soya, beef and palm oil.

As well as regional differences, a nation's deforestation drivers may vary according to their forest transition stage. Across all classes of deforestation driver, their absolute net contribution to deforestation is greatest during the early transition phase when most deforestation occurs (Hosonuma et al., 2012). However, their relative importance may shift. For example, some authors state that progress along the forest transition reflects economic growth and the expansion of the non-farm sector. It is proposed that this is reflected in a higher proportion of deforestation being driven by infrastructure and urban expansion, in the post-transition phase (Angelsen and Rudel, 2013).

Overall, there is clear evidence of the primacy of agriculture in driving global and tropical deforestation. Knowledge gaps remain, including information on the relative contribution of different types of agriculture and of other drivers, in less-studied regions and countries, particularly in Africa. Knowledge on the relative contribution of different agricultural products and on the interaction between agriculture and other deforestation drivers, is also incomplete. The thesis seeks to contribute to addressing these knowledge gaps.

1.1.4 Drivers of forest regeneration

Drivers of forest regeneration have received less research attention than drivers of deforestation. Definitional differences have contributed to this. There are significant gaps in our knowledge of forest regeneration drivers.

Enhancing forest carbon stocks has been promoted through the UNFCCC since the Bali Action Plan was adopted, in 2007 (2/CP.13). In 2009, Parties agreed '*To identify activities within the country that result in… increased removals, and stabilization of forest carbon stocks*.'

Despite the inclusion of activities that result in enhanced forest carbon stocks in the UNFCCC process, regeneration drivers have received less research attention than deforestation drivers, again with the greatest knowledge gaps for Africa (Borda-Niño et al., 2020). Most studies of regeneration drivers have focused on the variables that affect vegetation growth or biomass / carbon sequestration rates per unit area, in regenerating forests (Crouzeilles et al., 2016; Heinrich et al., 2021; N'Guessan et al., 2019). These studies are discussed further in Section 1.1.5.

Other studies consider the drivers of an expansion in gross or net tropical forest cover such as Borda-Niño, Meli, and Brancalion (2020) and Rudel et al. (2016), respectively. These studies have found that a combination of biophysical factors including precipitation, steep slopes and proximity to forest fragments, and socio-economic factors including proximity to settlements, presence of protected areas, cereal yield and percentage of the economically active population in agriculture, had the greatest influence on the expansion of tropical forest cover. A nation's deforestation rate was the most important explanatory variable for tree cover gain. Countries with high deforestation rates, also have high rates of tree cover gain. In these studies, the relative influence of different factors is mostly determined through regression analysis of remote sensing and other spatial data. Their definition of a driver of natural forest regeneration is more similar to the definition used in this thesis than the biomass accumulation determinants of e.g. Crouzeilles et al. (2016). However, while Borda-Niño, Meli, and Brancalion (2020) consider a broad set of variables that affect the rate of forest cover increase, this thesis focuses on the trigger that results in a transition from non-forest to forest such as a farmer deciding to abandon an area of agricultural land or begin fallowing, or a community deciding to restore an area of forest.

These three regeneration drivers: agricultural land abandonment, conservation and fallowing, have been recognised in previous studies, albeit without being grouped as 'regeneration drivers' as outlined below.

The **abandonment of agricultural land** is a regeneration driver that received early attention in the development of the Forest Transition Model. In their description of the theoretical basis for the model, Mather and Needle (1998) stated that that '*the progressive adjustment of agriculture to land capability*' would cause land to be '*released from agriculture,… thus becoming available* *for reforestation (by regeneration or planting)*.' In other words, as farmers become more familiar with their land, they focus their efforts on the most productive land, leaving less productive land for other uses, including forests. This is most noticeable in the post-transition forest expansion phase but they also modelled its presence in the high deforestation phase of the model where farmers abandon marginal agricultural land in favour of more productive land, even as the overall forest area declines. Building on Mather and Needle's work, Rudel et al. (2005) suggested that another key reason for expanding tree cover in the post-transition phase was '*forestation*' in countries where deforestation had decimated natural forests but whose population depended on wood products. While this is often achieved through plantations of exotic species, as in the case of China, they also described initiatives to increase wood supply through the restoration of degraded community-managed forests in India. This points to another key regeneration driver i.e. **conservation**. The role of conservation and restoration in the forest transition have been magnified, over the last twenty years, as forests' climate-change and biodiversity-loss mitigation potential are valued and monetised, including through REDD+ (Atmadja et al., 2022; Rudel et al., 2020).

Agricultural fallows, in areas where shifting cultivation or swidden agriculture is practised, are a third class of regeneration driver. Farmers integrate fallows into their farming practices for multiple reasons primarily weed suppression and restoring soil fertility (Ickowitz, 2006). Fallows are used as signatures of shifting cultivation in global remote sensing analyses (Heinimann et al., 2017) and of tree cover loss due to shifting cultivation (Curtis et al., 2018). Globally, there is a decline in the area of land under shifting cultivation, primarily due to agricultural intensification (Heinimann et al., 2017). The decline is most pronounced in south-east Asia, while the trend in Africa and Latin America is more variable (Molinario et al., 2015). For example, in the Democratic Republic of the Congo, Molinario et al. (2017) found that 60% of land in the agricultural mosaic zone, comprised fallows or secondary forest. Since fallow duration affects the likelihood that an area will reach 'forest' status, changes in fallow length also affect fallowing's potential as a driver of natural forest regeneration. Agricultural intensification is associated with shorter fallow-times (Boserup 1965). Reductions in fallow length have been widely observed across the tropics (Jakovac et al., 2017; van Vliet et al., 2012).

For most countries, data on the relative contribution of different regeneration drivers is not available. Understanding the reasons for land to transition from non-forest to forest is useful for restoration efforts. For example, an understanding of why farmers allow land to fallow for sufficiently long that secondary forest develops and of the livelihood and climate implications of longer fallows, could be integrated in restoration initiatives (Van Vliet et al., 2013; Ziegler et al., 2012). While the main drivers of deforestation can usually be deduced from remote sensing data, the direct drivers of regeneration often require field surveys and interviews with land users in order to determine the motivation for land to convert from non-forest to forest. This has contributed to a paucity of data on regeneration drivers.

By investigating the prevalence of direct regeneration drivers, including the three drivers considered above, the thesis aims to shed light on the activities and actors that lead to natural forest cover gain, even in areas of net deforestation.

1.1.5 Biomass and species accumulation rates in regenerating tropical forests

The accumulation rate of biomass, and its component carbon, determine the climate change mitigation and wood-harvesting potential of a regenerating forest. Rates have been measured by assessing changes in biomass over time in long-term monitoring plots (Chidumayo, 2013); using a chronosequence approach (Spracklen and Righelato, 2016); and comparing time series of appropriate remote sensing data (McNicol et al., 2018).

Biomass accumulation rates vary significantly with the highest rates, globally, in young secondary African tropical forests (7.6 Mg ha^{-1} y^{-1}) (Requena Suarez et al., 2019). Compared with other parts of the world there is a paucity of data on biomass accumulation rates for Africa (Anderson-Teixeira et al., 2021).

Species recovery rates are similarly variable. In the Amazon, bird, plant and dung-beetle species richness recovered at a rate of 2.6% per year in regenerating secondary forests, compared with undisturbed primary forests

(Lennox et al., 2018). Different taxonomic groups recover at different rates. Compared with a range of vertebrate and invertebrate taxa, tree and liana species assemblages were the slowest to recover in north-eastern Amazonia (Chazdon et al., 2009).

Biomass and species accumulation rates are influenced by multiple factors. In a meta-analysis of forest restoration studies, Crouzeilles et al. (2016) found that '*time elapsed since restoration began, disturbance type and landscape context*' were the main determinants of forest restoration success, defined as a return to the biodiversity and structure of equivalent old-growth forest.

The relative importance of determinants differs between biomass and biodiversity and depend on the scale of analysis. At a regional scale, precipitation is a strong determinant of biomass recovery. For example, in Neotropical secondary forests, rainfall has a stronger positive effect on biomass recovery than regeneration time (Poorter et al., 2016). At a local scale, regeneration time and land use history are key determinants of biomass accumulation. For example, in a study near Kisingani in the Democratic Republic of the Congo, biomass increased with regeneration time but those biomass gains declined with each successive cultivation-fallow cycle (Moonen et al., 2019). Species accumulation rates are linked to biomass accumulation (Lennox et al., 2018) but are also affected by landscape connectivity and proximity to source populations (Mayhew et al., 2019).

With a view to increasing understanding of the climate and biodiversity values of naturally regenerating forests, the thesis examines extent, rates and determinants of biomass and tree species accumulation in Tanzania.

1.1.6 Agriculture and forest policy

While national governments and the United Nations aim to reduce net emissions of greenhouse gases from forest biomass change (UNFCCC, 2015), there is uncertainty on different policies' impact and on how to manage trade-offs between forests and agriculture (Carter et al., 2018).

Competition for land between agriculture and forests underpins most deforestation. As a result, a key policy issue is how to balance land allocation between agriculture and forests, particularly in the context of growing global demand for food and other agricultural commodities.

Green (2005) compared two options for achieving a balance between increased food production and biodiversity conservation:

1. Land sharing: biodiversity conservation and agricultural production objectives co-occur in a shared space. This boosts biodiversity values on agricultural land but reduces agricultural yields. Long-fallow shifting cultivation has been proposed as one approach to land-sharing that can integrate biodiversity and carbon sequestration into agricultural landscapes (Mertz et al., 2021).

2. Land sparing: through agricultural intensification, yields per unit area increase thereby reducing the amount of land that is needed for agriculture. The land that is spared from agricultural production is designated for biodiversity conservation. Biodiversity conservation and agricultural production occur in separate spaces. This reduces biodiversity values on agricultural land but increases agricultural yields.

While there is no simple or single response to this (Kremen, 2015; Mertz and Mertens, 2017), there is some recognition that a combination of the two approaches ‘land-shparing’ is needed and that the balance between the two approaches will vary with place / context and scale (Balmford et al., 2018; Law and Wilson, 2015). While the land sharing / sparing debate has focused on biodiversity, it links with a growing body of research on the integration of carbon sequestration in agriculture through approaches such as climate smart agriculture and conservation agriculture (Prestele and Verburg, 2020). Using legal or fiscal policy tools, governments can and do influence the forest-land-agriculture nexus, including through REDD+ (Angelsen and Rudel, 2013).

The thesis aims to contribute to this area of research in two ways. Firstly, by presenting empirical evidence on the extent to which agriculture and deforestation are inter-connected, the thesis points to the importance of addressing the forest-land-agriculture policy nexus, in Tanzania. Secondly, by documenting the rates and drivers of regeneration in agricultural landscapes, the thesis provides new insights on carbon sequestration and biodiversity values of agricultural land.

1.1.7 Energy policy

Many countries have sought to reduce deforestation by adopting policies to reduce charcoal use based on an assumption that charcoal drives deforestation (Leach, 1992; Zulu, 2010). Globally, in 2020, 228 million people[2] used charcoal as their primary fuel and 53 million tonnes of charcoal were produced, including 35 million tonnes produced in Africa (FAOSTAT, 2022). Despite its popularity many countries strive to transition away from charcoal use due its negative impacts on the environment, health and governance (Branch and Martiniello, 2018; Roy, 2019; Sola et al., 2017). While Chidumayo and Gumbo, (2013) attributed 7% of tropical deforestation to charcoal, other authors consider charcoal to be a driver of forest degradation, rather than deforestation (Hosonuma et al., 2012).

The energy transition model underpins energy policy in many countries. The energy transition model states that households substitute biomass fuels with ‘modern energy sources’ as household incomes increase and urban areas expand (Leach, 1992). Modern energy sources include Liquefied Petroleum Gas (LPG), kerosene and electricity. The model assumes that households prefer modern energy sources and that accessibility and income are the two major barriers to use. However, subsequent studies have found that, with increased income, households often diversify cooking fuels without abandoning charcoal, a practice known as fuel-stacking (van der Kroon et al., 2013).

As a deforestation reduction policy tool, the promotion of the energy transition has three key flaws. Firstly, it does not address the main driver of deforestation which is agriculture (Curtis et al 2018). Since charcoal is rarely a driver of deforestation on its own, reducing charcoal use is unlikely to reduce deforestation. Secondly, the model of increased incomes resulting in reduced charcoal use is not borne out by empirical evidence which points to fuel-stacking as a more common scenario (Hiemstra-van der Horst and Hovorka, 2008; Masera et al., 2000). Thirdly, the problematisation of charcoal, that can

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[2] https://www.who.int/data/gho/data/indicators

accompany an energy transition policy, impedes initiatives promoting more sustainable charcoal. This includes initiatives seeking to incentivise reduced deforestation by directing revenues from sustainable charcoal production into forest management (Branch et al., 2022; Munro, 2017). In this way, the ‘energy transition as forest conservation strategy’ not only fails to address the real driver of deforestation, it can also undermine sustainable forest management. The thesis aims to contribute to this area of research by looking at the relationship between Tanzania’s energy-transition based energy policy and rates and drivers of deforestation.

1.2 Tanzania as a case study

Tanzania was selected as the focus for the study as it is a high deforestation country with uncertain deforestation and regeneration rates, and a lack of quantitative data on drivers of deforestation and regeneration. Tanzania has the third largest forest area in Africa, and the fifth highest mean annual net forest cover loss in the world (FAO, 2020a). Tanzania has also tried unsuccessfully to reduce deforestation by restricting, and periodically banning, charcoal trade and use (Mabele, 2020).

1.2.1 Background to Tanzania

Located on the East African coast, the United Republic of Tanzania comprises Mainland Tanzania (88.3 Mha) and the semi-autonomous islands of Zanzibar (0.25 Mha).

The 2022 census recorded a population of 61,741,120 and a mean annual population growth rate (2012 – 2022) of 3.2%. Dar es Salaam, the commercial capital, is the most populous region with 5,383,728 people. Its growth rate slowed from 5.6% (2002 – 2012) to 2.1% (2012 – 2022), a rate lower than previous projections. The capital of Tanzania, Dodoma, grew by 3.9% (2012 – 2022) and has a population of 3 million people (National Bureau of Statistics, 2022).

Key administrative layers are sub-villages, villages, wards, districts and regions. At village level, decisions can be made about land use and enforced through by-laws.

There are three classes of land, according to the Land Act 1999 (United Republic of Tanzania, 1999). Village land (70%) is land under the authority of Village Assemblies. Reserved land (28%) includes all protected areas except village land and community forest reserves. General land (2%) is a residual class including privately owned land and urban areas.

Mainland Tanzania, formerly Tanganyika, gained independence from Britain in 1961, uniting with Zanzibar to form the United Republic of Tanzania in 1964. The ruling party, Chama Cha Mapinduzi, have remained in power since independence. National elections are held every five years.

GDP grew by 4.3% in 2021 (World Bank Group, 2020). Agriculture is the main economic activity for 58% of the population but accounts for only 28% of GDP. Although Tanzania transitioned from a low- to low-middle income country in 2020, there is still widespread poverty with 49% of the population living on <US$ 1.90 person^{-1} day^{-1} (ibid).

1.2.2 An overview of forests in Tanzania

There are approximately 45 – 48 Mha of forest in Tanzania, the third largest area of forest in Africa after Angola and the Democratic Republic of the Congo (FAO, 2020a). Tanzania's montane and coastal forests have exceptional levels of biodiversity (Burgess et al. 2007a; Burgess et al. 2017; Rovero et al. 2014).

Natural forests provide products and services vital to the livelihoods of millions of people, in Tanzania. The most widely used forest product is fuelwood, used by 63% of all households (United Republic of Tanzania, 2020). Food, construction materials and medicines are other widely-used natural forest products (United Republic of Tanzania Ministry of Natural Resources and Tourism, 2015). As in other tropical countries, forests and trees are important for livelihood and food system resilience (Ickowitz et al., 2022).

Tanzania has a high diversity of forest habitats. Two classification systems for Tanzanian vegetation are widely used: the species-based classification developed by White (1983); and the physiognomic classification used by the FAO Global Forest Resource Assessment (GFRA) and by Tanzania's National Forest Resources Monitoring and Assessment (NAFORMA). Based on levels of endemism, White classified Tanzania's vegetation into five phytochoria including four centres of endemism: the Afromontane archipelago, Zambesian, Somali-Masai and Zanzibar-Inhambane, plus the Lake Victoria regional mosaic. Within these phytochoria, he identified different vegetation types including forest, wet and dry miombo woodland, bushland and thicket. In contrast, the FAO and NAFORMA classification considers the physiognomic characteristics of vegetation. For Tanzania, in order of extent, the most widespread forest classes are open woodland (10 – 40% canopy), closed woodland (>40% canopy), bushland, lowland forest and thicket (Mauya et al., 2019). In order to align the research with national datasets, including NAFORMA vegetation maps, the thesis follows the FAO / NAFORMA classification. With 26.3 Mha of forest in protected areas (United Republic of Tanzania, 2017), Tanzania has the 8th largest area of forest in protected areas globally and the 2nd highest area in Africa (FAO, 2020a). According to the GFRA, out of 45.2 Mha of natural forest in Tanzania (excluding plantations and other planted forests), 28.5 Mha are primary forest indicating that approximately 13.7 Mha are secondary or degraded forests (FAO, 2020b).

1.2.3 Forest cover change in Tanzania

Tanzania had the fifth highest average annual net loss of forest area (2010 – 2020) in the world (after Brazil, Democratic Republic of Congo, Indonesia and Angola), according to the latest FAO Global Forest Resources Assessment (FAO, 2020a).

Tanzania is in the early transition phase of the Forest Transition Model (Hosonuma et al., 2012). With ~48.1 Mha of forest in 2011, forest cover was approximately 54.4% of the 88.3 Mha of the land that comprises mainland Tanzania (excluding the islands of Zanzibar) (United Republic of Tanzania Ministry of Natural Resources and Tourism, 2015).The national definition of forest is an area of ≥0.5 ha with ≥10% canopy cover of trees ≥3 m in height (United Republic of Tanzania, 2002).

As an early transition country, the rate of deforestation is accelerating (Hansen et al. 2013; United Republic of Tanzania Ministry of Natural Resources and Tourism 2015), although estimates of the national deforestation rate differ. In Tanzania's Forest Reference Emission Level (FREL) submission to the United

Nations Framework Convention on Climate Change (UNFCCC) in 2017, the gross deforestation rate is calculated to be 0.469 Mha y^{-1} for the period 2002 – 2013 with only 32 Mha of ‘forest remaining forest’ (p. 18). A much lower rate of 0.166 Mha y^{-1} (2000 – 2012) was calculated by Hansen et al. 2013, using Landsat data, while the latest Global Forest Watch data for 2011 – 2020 indicate a tree cover loss of 0.224 Mha y^{-1} taking a 10% canopy cover threshold (Hansen et al. 2013 v20200331). This wide range in estimates is reflected in Tanzania’s national report to the FAO GFRA which indicates a deforestation rate of 0.13 – 0.5 Mha y^{-1} (FAO, 2020b), with a net annual deforestation rate of 0.42 Mha y^{-1} adopted in the global report (FAO, 2020a). Differences between the Landsat-based estimates and Tanzania’s own estimates have been attributed to different canopy cover thresholds and the challenges of comparing estimates based on Tanzania’s sample-based field inventory with Landsat-derived data with lower accuracy in low biomass vegetation types with high seasonal variability (Ortmann et al., 2015). The small size of many deforestation events, in Tanzania, may also contribute to under-estimation in the Hansen dataset (Hamunyela et al., 2020). In contrast, the deforestation rate recorded by McNicol, Ryan, and Mitchard (2018), using Phased Array L-band Synthetic Aperture Radar (PALSAR) data combined with field surveys, was much higher at 1.4 Mha y^{-1} (2007 – 2010). The order of magnitude divergence in estimates of the rate of gross deforestation in Tanzania indicates an area of scientific uncertainty with implications for national and international measurement, reporting and verification including in the context of the UNFCCC. Reducing uncertainty around Tanzania’s deforestation rate is one rationale for the thesis.

There is even greater uncertainty on the rate of regeneration. Ortmann et al., (2015) estimate a gross gain in forest and woodland area of 0.008 Mha y^{-1} (1990 – 2000), decreasing to 0.005 Mha y^{-1} between 2000 – 2010, as also reported for 2015 – 2020 in the Global Forest Resources Assessment (FAO, 2020b) while Hansen et al. (2013) calculate a rate of 0.025 Mha y^{-1} (between 2000 – 2012). Localised studies report rates of 4% (2000 – 2011) in southern woodlands (Solberg et al., 2015) and 2.4%[3] (2001 – 2017) in Eastern Arc Mountain forests, in Morogoro Region (Hamunyela et al., 2020).

Due to uncertainty over the extent of regenerating forests, carbon sequestration from forest regeneration was excluded from Tanzania's 2017 FREL. Although McNicol, Ryan, and Mitchard (2018), looked at the area of forest that gained biomass, they did not look at areas transitioning from non-forest to forest. In their study, areas that were non-forest (i.e. having an Above-Ground Carbon density <10 Mg C ha^{-1}) at the start of their study period were excluded from the analysis. For areas that were forest in 2007, they recorded gains of 55.7 Tg C across 18.7 Mha of forest, providing an indication of the significant contribution of forest growth to Tanzania's carbon sequestration rate.

1.2.4 Drivers of deforestation in Tanzania

While agriculture is known to be the main driver of deforestation in Tanzania (Curtis et al., 2018; Nzunda and Midtgaard, 2019; Willcock et al., 2016), there has been confusion over the relative contribution of different drivers, particularly charcoal (Mwampamba et al., 2013; Nzunda and Midtgaard, 2019). Tanzania's National REDD strategy provides nominal data on deforestation and forest degradation drivers. The list includes '*settlement and agricultural expansion, overgrazing, firewood and charcoal production, uncontrolled fires, timber extraction, infrastructure / industry, mining, refugees and…biofuel production*' (United Republic of Tanzania, 2013). However, the document also notes, '*the relative importance of these factors to Deforestation and forest Degradation and eventually to global GHG emissions has not been determined*.'

More recently, Pendrill et al. (2022) estimated that agriculture-driven deforestation comprised an average of 110,000 – 150,000 ha y^{-1} out of a total deforestation of 120,000 – 160,000 ha y^{-1} between 2011 – 2015.

[3] They report regeneration on 9% (1,843.8 ha) of a disturbed forest area of 20,487 ha out of a total study of 75,735 ha equivalent to 2.4% of the total study area.

In contrast, Chidumayo and Gumbo, (2013) estimated that charcoal caused 33.16% of Tanzania's deforestation, the highest rate of charcoal-driven deforestation in the world.

Reducing uncertainty around the relative contribution of deforestation drivers is an objective of the thesis.

1.2.5 Drivers of regeneration in Tanzania

While shifting cultivation is known to be a regeneration driver in Tanzania, there is uncertainty around the extent of shifting cultivation and fallowing practices. Heinimann et al. (2017) suggest an increase in shifting cultivation in central and southern Tanzania, a decrease around Lake Victoria, with persistence elsewhere, while case studies from eastern-central Tanzania show a decline in extent, and in the number of shifting cultivators (Kilawe et al., 2018).

The presence of other regeneration drivers such as conservation and the abandonment of marginal agricultural land can be assumed but empirical data on their extent, are unavailable. Generating new data on the relative contribution of regeneration drivers is an objective of the thesis.

1.2.6 Biomass accumulation in regenerating forests in Tanzania

Determining the carbon balance of natural woodlands requires an understanding of carbon stocks; carbon losses through deforestation and forest degradation; and carbon gains through regeneration. Carbon stocks in miombo woodlands in Tanzania have been well studied (Lupala et al., 2014) and Tanzania's National Forest Inventory data indicate mean above ground carbon stocks of 43.7 t C ha^{-1} for lowland forest; 20.0 and 32.4 t C ha^{-1} for open and closed woodland respectively; 9 – 10 t C ha^{-1} for bushland; and 6.3 t C ha^{-1} for thicket (Mauya et al., 2019). NAFORMA data, and an increase in research interest, have also enhanced understanding of forest degradation (Nzunda and Yusuph, 2022). On average, 1.23 ± 0.37 t ha^{-1} y^{-1} are removed, with higher degradation rates on village land (1.45 ± 0.12 t ha^{-1} y^{-1}) (Manyanda et al., 2020), while McNicol et al (2018) estimated Tanzania's forest degradation losses at 18 Tg C y^{-1} (2007 – 2010).

Annual biomass accumulation rates for miombo woodlands range from 0.09 Mg ha^{-1} y^{-1} to 4.5 Mg ha^{-1} y^{-1} [4] (Chidumayo, 2013; Kalaba et al., 2013; McNicol et al., 2015). Variability between reported biomass accumulation rates is greatest for 20 – 30 year stands (Frost, 1996). Using studies from Zambia and Zimbabwe, Frost (1996) modelled stand biomass against stand age, concluding that biomass increases as a logistic function of the age of regrowth. While Frost's model indicated a maximum annual increment at around 18 years (Figure 2), Chidumayo (2013) found that the biomass increment rate continued to increase up to 23 years from the start of regeneration.

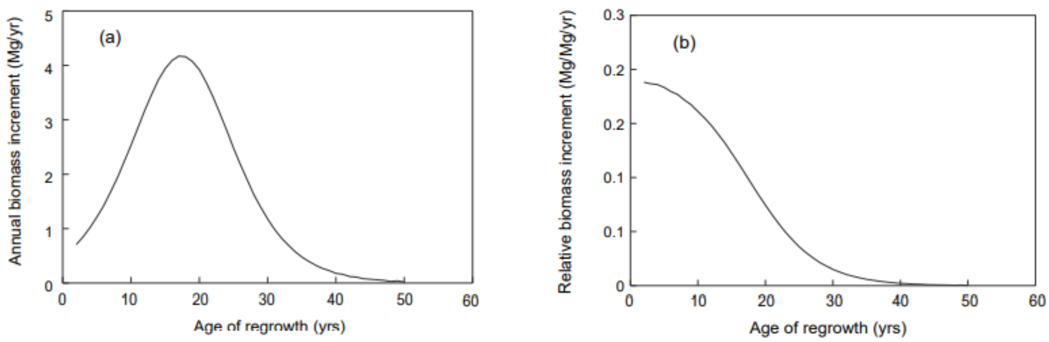

Figure 2 Total and relative annual biomass increment in miombo woodland

a) Annual biomass increment (Mg ha^{-1} y^{-1}) and b) relative biomass increment (Mg Mg^{-1} y^{-1}) estimated from the regression of stand biomass on stand age for various miombo woodland coppices plots. Source: (Frost, 1996)

In contrast, Kalaba et al. (2013) found that '*the sequestration rate was highest in the initial regeneration phase (up to 2.1 Mg C ha^{-1} in the first 5 years), and lowest in the oldest plots i.e. over 25 years (0.89 Mg C ha^{-1} y^{-1})*'.

[4] converting 2.1 Mg C ha^{-1} to 4.5 Mg biomass ha^{-1} yr^{-1} (Kalaba et al. 2013) by dividing by 0.47, the IPCC 2006 conversion factor.

Less data is available for lowland forest and bushland. In Kenya, in bushland dominated by *Acacia drepanolobium*, a biomass accumulation rate of 1.3 Mg ha^{-1} y^{-1} was recorded (Okello et al., 2001).

The stand age at which the maximum annual increment is reached is a key consideration in selecting harvesting cycles for timber and charcoal production as the maximum annual increment is often considered the optimal forest rotation (Newman 1988). However, stem size is also important. For example, charcoal producers generally select trees on the basis of stem size and species, preferring stems with a minimum dbh of 20 – 30 cm for charcoal with smaller stems as fuel and spacers (Chidumayo, 1993; FAO, 2017). Research in Zambian miombo woodlands reports a mean annual stem increment of 0.44 cm y^{-1} and 0.56 cm y^{-1} in post charcoal and post shifting cultivation regenerating woodlands (Syampungani et al., 2010). Based on these values, trees would require approximately 40 years to reach a desirable stem size of 20 cm dbh. However, it is possible to make charcoal from smaller stems, as is done in Zambia where a minimum stem size of 5 cm has been set (FAO, 2017). Similarly, FAO (1983) report that, in the iron industry, optimal wood pieces are 2.5 – 8.0 cm diameter. For stem sizes to reach 5 – 8 cm dbh would require a harvesting rotation of only 10 – 15 years.

As well as stand age, biomass accumulation rates are known to be affected by biophysical factors including vegetation type and connectivity, geology, soil, temperature and precipitation, herbivory, fire frequency and seasonality, and human disturbance type and intensity (Frost 1996; Chidumayo 2013; Mwampamba and Schwartz 2011). While precipitation and soil type are recognised to be key variables, the relative importance of other variables, in isolation or in combination, is poorly understood, a dynamic that this thesis explores.

1.2.7 Species accumulation in regenerating forests in Tanzania

How the biodiversity of a regenerating forest differs to the pre-deforestation forest gives an indication of deforestation's net biodiversity impact. As with biomass, this requires an understanding of the rate at which species accumulate over the course of regeneration.

In Tanzania and its neighbouring countries, most studies of biodiversity change in regenerating forests, have focused on changes in tree species diversity in miombo woodland. In general, studies have found that species accumulate to levels comparable to pre-deforestation forests after 10 – 35 years but species composition differs (e.g. Montfort et al., (2021)).

In Tanzania, the tree species richness of regenerating miombo reached levels comparable with mature woodland after 6 – 12 years, although species composition differed (McNicol et al., 2015). In lowland forests, species diversity reached 124% of old-growth forest in 17 – 31 y fallows with species accumulation rates peaking earlier in submontane than lowland forests (Mwampamba and Schwartz, 2011).

In neighbouring Mozambique, two studies found comparable levels of tree species diversity between 10 – 35 year-old shifting cultivation fallows and adjacent woodlands, while species composition differed (Montfort et al., 2021; Williams et al., 2008), with similar findings from Zambia (Chidumayo, 2013).

The species accumulation rate was 1.8 species y^{-1} up to six years; and 0.8 species y^{-1} at 35 years[5], in Mozambique (Montfort et al., 2021). In Zambia, the species accumulation rate was 0.7 species y^{-1} up to 10 years and 0.5 species y^{-1} at 22 years[6] (Chidumayo, 2013).

Less is known about dynamics in other vegetation types including bushland and lowland forest. In one Eastern Arc Mountain forest, tree species diversity recovered more slowly than biomass, following cultivation (Mwampamba and Schwartz, 2011).

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[5] Calculated using the species richness and mid-point age (5 years and 32.5 years respectively) for the results reported by Montfort et al 2021 who state that '*Woody species richness … increased with time after abandonment from 9.0 ± 4.0 species (at 4–6 years old) to 26.4 ± 11.8 species (at 30–35 years old).*'

[6] Calculated using the species richness and stand age (5 years, 10 years and 22 years respectively (plots were cleared in 1990/91) for the results reported by Chidumayo 2013 who states '*Overall species richness increased from 3.4 ± 0.95 in 1995 to 7.2 ± 0.95 in 2000 to 11.3 ± 1.06 in 2012 ($r2 = 0.70$, $P < 0.0001$).*'

Factors influencing the rate of species recovery in Tanzania and neighbouring countries include landscape level disturbance, with a steep decline in species recovery when land use intensification affects >75% of a landscape (Tripathi et al., 2021). Cultivation time has also been identified as a key factor, with little regeneration in land cultivated for >16 y (Mwampamba and Schwartz, 2011). There is uncertainty on the relative influence of different factors on species accumulation rates, and variability between vegetation types. Factors affecting changes in tree species richness, in regenerating natural forests, are examined in the thesis.

1.2.8 Policy

Protected areas are Tanzania's main policy tool in avoiding deforestation. Approximately 50% of forests are in protected areas, while only 21% of deforestation occurred in reserved areas[7]. In general, protected areas have been successful in conserving forests, with localised evidence of increasing effectiveness (Hamunyela et al., 2020; Willcock et al., 2016).

Outside of protected areas, and in the absence of data on the relative contribution of different deforestation drivers, there has been an emphasis on reducing charcoal use as a way to reduce deforestation (Mabele, 2020). Tanzania's three national energy policies have promoted a transition towards electricity and fossil fuels and away from charcoal and firewood (United Republic of Tanzania, 2015, 2003, 1992). Charcoal bans and a tax exemption on Liquefied Petroleum Gas (LPG), an alternative cooking fuel, have been some of the policy tools used to reduce charcoal use (Sander et al., 2013). These interventions have caused economic losses and conflict. They have also undermined attempts to expand community-based forest management, the cornerstone of national policy to reduce deforestation on village land, despite recent success in financing CBFM using sustainable charcoal revenues (Branch et al., 2022; Mabele, 2020).

Debates around the technicalities of sustainable charcoal production, particularly the timing of harvesting rotations, have also impeded a shift

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[7] 97,101 ha y-1 out of 469,000 ha y-1 based on Tanzania's 2017 FREL.

towards more sustainable charcoal. Understanding biomass accumulation rates and the factors that affect them, in naturally regenerating woodlands, is central to these debates. The thesis aims to contribute to these ongoing policy discussions.

1.3 Aims, objectives and thesis structure

1.3.1 Aim

The aim of the thesis is to determine the rates and drivers of deforestation and natural forest regeneration, in Tanzania. With one of the highest deforestation rates, globally, the thesis aims to provide a more nuanced understanding of Tanzania's forest cover change dynamics. The thesis is policy-facing, addressing ongoing policy issues including: the effectiveness of Tanzania's energy policy in reducing deforestation through energy transitioning; the forest-agriculture-land policy nexus on village land; and the role of sustainable charcoal production in forest policy.

1.3.2 Objectives

With a focus on Tanzania, the objectives of the thesis are:

Objective 1. To determine the rate and drivers of deforestation.

Objective 2. To determine the rate and drivers of natural forest regeneration on village land.

Objective 3. To develop new methods to assess rates and drivers of deforestation and natural forest regeneration.

Objective 4. To assess the effectiveness of a deforestation-reduction through energy-transition policy.

1.3.3 Thesis structure

The thesis follows the protocol for the format of an alternative style of doctoral thesis and includes three published papers in Chapters 3 – 5.

In **Chapter 2**, the research methods are described. While descriptions of methods are also included in Chapters 3 – 5, due to journal word limits, these are necessarily brief. This chapter provides a more elaborate description of the methods and approach used in the study. It highlights a novel method to quantify forest cover change (deforestation and regeneration); and innovative ways of combining remote sensing and field survey methods to understand drivers of forest cover change.

Chapter 3 determines the rate and drivers of deforestation, in Tanzania. Given Tanzania's policy of reducing deforestation through energy transitioning, the research was designed to provide new data on the relative contribution to deforestation of agriculture, charcoal and other drivers. It comprises the following publication that represents the first national, empirical study of the proximate drivers of deforestation for Tanzania based on a combination of remote sensing, ground surveys and interviews:

Doggart, N., Morgan-Brown, T., Lyimo, E., Mbilinyi, B., Meshack, C.K., Sallu, S.M., Spracklen, D.V., 2020. Agriculture is the main driver of deforestation in Tanzania. Environmental Research Letters 15, 034028.

https://doi.org/10.1088/1748-9326/ab6b35

Chapter 4 determines the rate and drivers of regeneration across Tanzania's village land and explores reasons for differences in biomass and species accumulation rates, in regenerating forests. Compared with deforestation, forest regeneration is a poorly understood dynamic, particularly in Africa. By combining remote sensing and field survey data, Chapter 4 provides new insights into forest regeneration drivers, an emerging field of research. Chapter 4 also provides new biomass accumulation data for three vegetation types under real-world conditions which can be used for multiple purposes including improving the accuracy of global change models, forest restoration planning and sustainable harvesting for charcoal or timber. It comprises the following publication:

Doggart, N., Mugasha, WA., Mpiri, A., Morgan-Brown, T., Sallu, S.M., Spracklen, D.V., 2023. Agricultural fallows are the main driver of natural forest regeneration in Tanzania. Environmental Research Letters 18, 054008.

https://doi.org/10.1088/1748-9326/accbd6

Chapter 5 examines the effectiveness of energy policy objectives to reduce deforestation by encouraging an energy transition for households, and considers how national energy policy could contribute more to national and international climate change mitigation and sustainable energy goals. Using new data on household cooking-fuel use, Chapter 5 provides a fresh perspective on how and why the policy of reducing deforestation through energy transitioning, has been ineffective. It comprises the following publication:

Doggart, N., Ruhinduka, R., Meshack, C.K., Ishengoma, R.C., Morgan-Brown, T., Abdallah, J.M., Spracklen, D.V., Sallu, S.M., 2020. The influence of energy policy on charcoal consumption in urban households in Tanzania. Energy for Sustainable Development 57, 200 – 213.

https://doi.org/10.1016/j.esd.2020.06.002

Chapter 6 provides a critical discussion of the research, linking the key findings from Chapters 3 – 5; highlights implications for forest management and policy; and sets out recommendations for future research. A conclusion summarises the findings and relevance of the thesis.

Appendices 1 – 3 include supplementary material linked to the three publications in Chapters 3 – 5.

Appendix 4 presents two policy briefs used to communicate the policy implications of the research in Chapters 3 and 4.

1.4 Motivation and background to the research

The research presented in the thesis has its roots in my work with the Tanzania Forest Conservation Group (TFCG). Prior to undertaking a PhD, I worked in Tanzania for over 20 years as Technical Advisor to TFCG. TFCG is a national Non-Governmental Organisation whose mission is '*to reduce poverty and to conserve and restore the biodiversity of globally important forests in Tanzania for the benefit of the present and future generations*.' My role with TFCG was to provide technical guidance and back-stopping to project managers involved in projects on participatory forest management, REDD+, environmental education, rural livelihoods, advocacy and research. Through my work with TFCG I become increasingly aware that village land forests were being cleared for agriculture while policies were focused on reducing charcoal use. With my colleague, Charles K. Meshack, we examined this in Doggart and Meshack 2017. However, evidence-based advocacy to align forest management and policy with the actual deforestation drivers was limited by a lack of data. In addition, I was intrigued by the potential for woodlands to be managed for sustainable charcoal production, providing an incentive for community-based forest management and improving rural livelihoods. These were key motivations for undertaking the research. The research was implemented in the context of three projects connected with these goals. Financed by the Critical Ecosystem Partnership Fund, the first project '*Reducing charcoal's threat to biodiversity: government mainstreaming of sustainable charcoal production in energy-sector policy tools*' set out to document the rate and drivers of deforestation, as set out in Chapter 3. The second project 'Transforming Tanzania's Charcoal Sector' set out to assess the rate and drivers of natural regeneration with a view to linking this to integrating sustainable charcoal production in community-based forest management areas, as set out in Chapter 4. The third project, was a 'baseline report on the charcoal market in Dar es Salaam', prepared for the World Bank, examining the effectiveness of policy tools promoting an energy transition in household cooking fuels, as described in Chapter 5. Linking my research with these ongoing projects has had the advantage that the research findings can be directly applied in ongoing advocacy, capacity building and direct conservation work. This is compatible with my solutions-oriented research approach. It has also necessitated vigilance to avoid bias and adhere to academic standards, throughout the research cycle.

The PhD was undertaken between January 2019 and December 2022. From 2020, it coincided with the global COVID-19 pandemic. As a result of global travel bans, there was limited opportunity to undertake field work in 2020 and 2021 which precluded my participation in the field work for Chapter 4.

The thesis is based on a belief that science can nudge humanity toward a future compatible with the survival of Earth's universally unique biodiversity, including ourselves. It is my hope that the research presented here can, in some small way, contribute to slowing Tanzania's deforestation rate and helping more of its unique natural forest to survive the forest transition.

Chapter 2 Methodology

This section provides a brief overview of the three key methods used in the research, with a focus on the rationale for their selection and areas of innovation.

Descriptions of the methods used in Chapters 3 – 5 are included in the respective chapters. Additional information is provided in Appendices 1 – 3. The appendices include the supplementary material for the three papers.

The thesis primarily comprises quantitative research. Some qualitative methods were also employed including text analysis and exploratory interviews for Chapter 5.

The thesis is interdisciplinary with connections to remote sensing, ecology, development studies, energy studies, forestry and policy analysis. Interdisciplinary research integrates elements from different disciplines. By crossing disciplinary boundaries, while setting common research goals, integrated knowledge and theory are created with relevance across the disciplines (Tress et al., 2005).

The research is solutions-oriented and designed to contribute to policy dialogue. Solutions-oriented research has '*a scientific focus on developing, evaluating, informing and advising society on the potential pathways for sustainable development*,' (DeFries et al., 2012).

The research explores the forestry – agriculture – land – energy policy nexus. A nexus approach focuses on the '*inter-linkages and competition for resources between different sectors of the economy and highlights the implications on development of (un)coordinated decision-making and management in these sectors*,' (Johnson and Karlberg, 2017).

The geographical focus of the research is Tanzania. However, the findings have relevance to other early forest-transition countries.

2.1 Remote sensing

Remote sensing data was used in all three papers.

For Chapter 3, a forest cover change analysis (2010 – 2017) was produced using data from the Phased-Arrayed L-Band Synthetic Aperture Radar (PALSAR) 2 on the Advanced Land Observing Satellite (ALOS) 2. PALSAR 2 is '*an active microwave sensor using L-band frequency to achieve cloud-free and day-and-night land observation*.'[8] It is particularly appropriate for forest cover change studies in low biomass African woodlands (Naidoo et al., 2016). Using the PALSAR 2 global mosaic product (Shimada et al., 2014), forest cover in 2010 was mapped across mainland Tanzania as anywhere with an HV backscatter DN value ≥ 2100 between 2007 – 2010 that was not classified as wetlands, water or flooded cropland in the NAFORMA Land Use Land Cover (LULC) map. This was then compared with HV backscatter DN values in 2015, 2016 and 2017. Areas, at least 6 pixels in size, mapped as forest in 2010 and where the DN value had declined by ≥15% to below 2100 by 2015, 2016 or 2017, were classed as deforestation. This gave the national deforestation rate estimate for Chapter 3. From the deforestation class, 120 random sample points were selected for the field survey (Section 2.2-3).

The accuracy assessment for the deforestation analysis was carried out in Google Earth Engine (Gorelick et al., 2017) using Landsat and Sentinel-2 images following the approach developed by Olofsson et al., (2013) (see A 1.1 for details). Images from Google Earth Pro were also used.

The potential to use Google Earth Engine to track land cover change on a year-by-year basis became clear while conducting the Chapter 3 accuracy assessment. This led to the development of the method applied in Chapter 4 and described in detail in Annexes A 2.1.1 and A 2.1.2. The method draws on four emerging trends in remote sensing: i. sample-based land cover change analysis; ii. time-series data; iii. use of multiple sensors; and iv. Google Earth Engine. The method combines these four emerging trends. Each of these emerging trends are examined briefly below.

Sample-based analysis: Land cover change using remote sensing data can be done using a 'wall-to-wall' mapping or a sample-based approach (or a combination of the two). Wall-to-wall mapping involves mapping the change

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[8] https://www.eorc.jaxa.jp/ALOS/en/alos-2/a2_about_e.htm

of every pixel in the area of interest. The Global Forest Watch dataset is the most widely used example of this (Hansen et al., 2013). A sample-based approach involves tracking the change of a sample of areas e.g. Achard et al., (2014). There are advantages and disadvantages to either approach. For the purposes of Chapter 4, the most relevant advantage of the sample-based approach is that it allows for a more granular investigation of land cover change than is possible with a wall-to-wall mapping approach. A sample-based approach has also been more effective in detecting deforestation in sub-Saharan Africa (Tyukavina et al., 2018), given well-documented challenges of southern African woodlands for remote sensing (David et al., 2022).

Time series data: While many land cover change analyses involve a comparison between two points in time (e.g. Hansen et al., 2013; Potapov et al., 2017), time series analyses are becoming increasingly popular (Woodcock et al., 2020). Time series tell a fuller story about how land cover changes over time. By telling a fuller story, they provide more precise evidence from which to identify the causes of change and to track gradual processes including regeneration. Chapter 4 used images from as many years as were available in Google Earth Engine, to track land cover change visually in 500 randomly selected sample points across village land, in Tanzania.

Use of multiple sensors: Using datasets from multiple sensors provides a richer source of evidence in determining land cover change.

Different sensors have different strengths and weaknesses. For example, Landsat has the advantage of a dataset that goes back to the 1980s. As an optical sensor it has the disadvantage that, whenever clouds are present, it cannot collect usable land cover data. As an active sensor, PALSAR, has the advantage that it collects data regardless of cloud-cover. However, in areas of steep topography, radar land cover data accuracy falls (Mitchard et al., 2012). By combining data from two optical sensors (Landsat and Sentinel 2) and one active sensor (PALSAR), the method developed in Chapter 4, provides a more robust way of detecting small gradual changes in land cover, including natural regeneration.

Google Earth Engine: This freely-available platform provides a user-friendly way to access multiple datasets simultaneously. The script linked to Section A 2.1.3 allows a layering of multiple datasets from different years which can be used to track change in a sample point. These were used in combination with historic high resolution data from Google Earth Pro and reference images for different land cover classes. A detailed description of the method, including a worked example, is provided in A 2.1.1.

The Chapter 4 dataset has the added advantage that it can regularly be updated to monitor the rate of forest cover change.

By combining these different emerging trends in remote sensing, the study offers a novel example of a user-friendly way to assess and monitor net forest cover change.

Although remote-sensing has provided the foundation for land cover change research, there are limits as to what can be deduced about land cover change from remote-sensing data alone. In the context of the research objectives of this thesis, remote sensing provided information on the rates of forest cover change. However, it was necessary to draw on other disciplines, including ecology and the social sciences, to understand the dynamics driving the observed land cover change.

2.2 Vegetation plots

Vegetation plots have been widely used in ecology. They are used to generate detailed information about an area's vegetation, that cannot yet be determined through remote sensing alone, including species composition, biomass and human activities. They have been widely used in Tanzania ((United Republic of Tanzania Ministry of Natural Resources and Tourism, 2015; Willcock et al., 2014). In the context of the thesis objectives, vegetation plots were needed to document signs of human activity (Chapters 3 and 4) and measure biomass and species composition (Chapter 4).

For Chapter 3, 120 survey points were randomly selected from the area mapped as deforestation (see Section 2.1), across mainland Tanzania. 25 m x 25 m square vegetation plots, centred on the selected pixel of deforestation, were assessed for vegetation cover and signs of disturbance. A broader 75 m x 75 m plot, centred on the same point, was assessed for evidence of charcoal-making. Tree species and biomass were not recorded since the research objective was to assess the drivers of deforestation. Data were recorded in the field on digital forms loaded onto the Open Data Kit application. 360° photographs were taken of all sample plots.

For Chapter 4, 180 field survey sample points (FSSPs) with regenerating forest, were identified, based on a clustered sampling approach. Clustered sampling has been widely used in forest ecology (Pellikka et al., 2018; Vågen et al., 2013). Ten sampling clusters were derived from the 500 random sampling points used in the remote sensing analysis described above (see also A 2.1.2 for details). For each cluster, 20 FSSPs with regeneration were identified visually, using remote sensing datasets. Of these 17 – 20 FSSPs per cluster were used in the final analysis.

At each FSSP, biomass and tree species were assessed in 15 m-radius circular vegetation plots following the standard methods used in Tanzania's Forest Inventory, NAFORMA (United Republic of Tanzania Ministry of Natural Resources and Tourism, 2010). The NAFORMA method was selected to allow for direct comparisons between Tanzania's national inventory data and the study data. 360° photographs were taken of all sample plots. The photographs were used for data validation and as evidence in understanding anomalous plots.

2.3 Structured interviews

Structured interviews were used in all three chapters. Structured interviews are designed to provide quantitative data, although some questions had open response fields to collect more qualitative data (Gravetter and Forzano, 2012).

The list of questions for the structured interviews that were used in Chapters 3, 4 and 5 are included in Appendices 1, 2 and 3 respectively. Interviews were administered in-person, in Swahili. Responses were documented using the Open Data Kit Application, on mobile phones.

In total, 1102 people were interviewed including 259 people for Chapter 3, 642 people for Chapter 4 and 201 people for Chapter 5. Between 1 – 5 people were involved in the interviews for each field survey sample plot (FSSP) (Chapters 3 and 4). Only one response per plot was recorded allowing for discussions between the interviewees until consensus was reached.

Interviewees were selected in consultation with local government staff and village leaders for interviews on village land (Chapters 3 and 4); and with protected area managers for plots on reserved land (Chapter 3). The key criteria for interviewee selection was familiarity with the FSSPs (Chapters 3 and 4). Where possible the person occupying or farming the sample plot was interviewed. If they were not available, then neighbours, or other people familiar with the area, were interviewed. In the case of the household surveys, in Chapter 5, households were selected based on a stratified random sampling strategy with strata for each of the study's five municipalities. Urban wards with a population density < 2,000 people / km^2 were excluded to avoid involving communities that are effectively rural albeit within an urban administrative area. The household closest to a random sample point was selected.

To ensure free, prior and informed consent, across each study (Chapters 3 – 5) enumerators provided an explanation of key aspects of the research before beginning each interview. This included information on how the data would be used and stored. Each respondent was asked whether they were willing to participate and the interview only proceeded once consent was given. Consent was given verbally and documented on the interview forms. At the end of the interview, respondents were again given the choice of withdrawing from the survey. Identifying characteristics have been removed from the datasets to preserve anonymity.

For Chapter 5, semi-structured interviews were carried out with six government staff, two representatives of Liquefied Petroleum Gas (LPG) distributors and one cooking-fuel briquette manufacturer. Semi-structured interviews allow for a more exploratory approach which was relevant in identifying different perspectives on energy policy options.

By combining the interviews with the vegetation plots and the remote sensing data (Chapters 3 and 4), the land cover change results can be triangulated. The interviews also provided a rich account of the land use history of each plot including details on agricultural outputs and farming techniques.

The combination of field survey and remote sensing data in Chapters 3 and 4 gives a more robust and detailed assessment of biomass, land cover change and drivers of deforestation and regeneration, than relying solely on remote sensing (Ahrends et al., 2021; David et al., 2022).

2.4 Novelty and contribution

With the objective of developing new methods to assess rates and drivers of forest cover change, Chapters 3 and 4 present two novel approaches to assessing deforestation and regeneration rates and drivers. Chapter 3 synthesizes methods from remote sensing, ecology and the social sciences to create a more coherent and comprehensive understanding of the direct drivers of deforestation. Chapter 4 draws on emerging areas in remote sensing to present a sample-based, time series method to assess deforestation and regeneration using Google Earth Engine. Again, taking an interdisciplinary approach, methods from ecology and the social sciences are used to analyse regeneration drivers and forest regeneration dynamics. An interdisciplinary approach to understanding land cover change has been widely recommended (IPCC, 2019). While it has been implemented for sub-national case studies (Llopis et al., 2019; Temudo and Santos, 2017; Wallenfang et al., 2015), no national-scale survey was found, that applies this approach.

The methods outlined in the survey have relevance beyond Tanzania. The method can be applied at national or sub-national level in any country. By using the freely-available, online Google Earth Engine, the method is easily accessible to researchers.

As well as contributing to methodological developments, the thesis presents new empirical evidence on

- rates and drivers of deforestation and regeneration in Tanzania;

- biomass and species recovery rates in regenerating woodlands, bushlands and lowland forests; and
- household cooking fuel use in Dar es Salaam.

By adopting a solutions-oriented approach, the research has contributed to policy dialogue, in Tanzania, on the role of charcoal in the national energy supply; the management of forests on village land; and policy interactions between the forestry, agriculture, energy and land sectors.

Chapter 3 Agriculture is the main driver of deforestation in Tanzania

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Agriculture is the main driver of deforestation in Tanzania

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Supplementary material for this article is available online

Abstract

Reducing deforestation can generate multiple economic, social and ecological benefits by safeguarding the climate and other ecosystem services provided by forests. Understanding the relative contribution of different drivers of deforestation is needed to guide policies seeking to maintain natural forest cover. We assessed 119 randomly selected plots from areas deforested between 2010 and 2017, in Tanzania. Through ground surveys and stakeholder interviews we assessed the proximate deforestation drivers at each point. Crop cultivation was the most commonly observed driver occurring in 89% of plots, compared to livestock grazing (69%) and charcoal (35%). There was evidence of fire in 77% of plots. Most deforestation events involved multiple drivers, with 83% of plots showing signs of two or more drivers. Stakeholder interviews identified agriculture as the primary deforestation driver in 81% of plots, substantially more than charcoal production (12%), timber harvesting (1%) and livestock (1%). Policy-makers in Tanzania have sought to reduce deforestation by reducing demand for charcoal. However, our work demonstrates that agriculture, not charcoal, is the main driver of deforestation in Tanzania. Beyond protected areas, there is no clear policy limiting the conversion of forests to agricultural land. Reducing deforestation in Tanzania requires greater inter-sectoral coordination between the agriculture, livestock, land, energy and forest sectors.

1. Introduction

Deforestation and forest degradation contribute to climate change (IPCC 2014, Baccini *et al* 2012, Scott *et al* 2018). Most net deforestation occurs in the tropics (Hansen *et al* 2013, IPCC 2014, Baccini *et al* 2017, Song *et al* 2018). National policies that aim to reduce deforestation will be more effective if they are informed by accurate and current data on deforestation drivers (Macedo *et al* 2012, Monteiro *et al* 2014). However, many countries have only nominal or ordinal information on the contribution of different deforestation drivers (Hosonuma *et al* 2012). To address this lack of information, the United Nations Framework Convention on Climate Change (UNFCCC) Conferences of Parties requests that Parties identify and address deforestation drivers (UNFCCC 4/CP.15, 1/CP.16, 15/CP.19).

A plethora of definitions exist for forest degradation and deforestation (Lund 2009, 2014, 2015). Deforestation is typically defined as the conversion of forest land to non-forest land (IPCC 2000). Forest degradation is typically defined as loss of forest quality, such as a reduction of aboveground biomass, in areas that remain forest. Proximate drivers of deforestation and forest degradation comprise the actions that directly result in a change in forest condition. Complex causal chains, involving an interplay of economic, political, social, demographic and biophysical pressures, contribute to the proximate drivers (Wehkamp *et al* 2015).

Multiple studies have found that commercial and subsistence agriculture are the main proximate deforestation drivers in tropical countries, with mining, infrastructure and urbanisation also contributing to deforestation (Geist and Lambin 2002, Busch and Ferretti-Gallon 2017, Wehkamp et al 2015). While agriculture for export markets now dominates deforestation pressure in southeast Asia (DeFries *et al* 2010), in Africa, subsistence agriculture and production for local markets are more important (Fisher 2010, Gibbs *et al* 2010, Kissinger *et al* 2012, Rudel 2013, Curtis *et al* 2018, De Sy *et al* 2019). Drivers of forest degradation include fuelwood collection, charcoal production, logging, uncontrolled fire and livestock grazing in forests, since they reduce biomass but do not result in the conversion of the land to a non-forest land use (Hosonuma *et al* 2012).

Tanzania, like many countries in sub-Saharan Africa, is experiencing ongoing deforestation and forest degradation. Tanzania is considered to be an early-transition phase country in the forest transition model (FTM), a trajectory from net-deforestation to net-reforestation that is observed in many countries (Mather 1992). Hosonuma *et al* (2012) define early transition countries as having forest cover between 15% and 50%, and an increasingly rapid rate of forest loss. Tanzania's forest cover is approximately 36% (32 Mha of forest in 2012, URT 2017) while the mean annual deforestation rate for the Tanzanian mainland increased from 1% between 1991 and 2000 (Matthews 2010) to 1.47% between 2002 and 2013 (URT 2017). If Tanzania were to follow the average FTM trajectory, forest area would decline to 13 Mha (15% of the land area), before reaching a post-transition reforestation phase. Inevitably, this would involve substantial losses of forest both inside and outside of protected areas (PA) with concomitant loss of biodiversity and other ecosystem services.

Various studies have explored drivers of deforestation in Tanzania. The global analysis of Curtis *et al* (2018) found that 93%–94% of tree cover loss (at >10% tree cover) in Tanzania between 2010 and 2015 was associated with shifting cultivation, 4%–5% with forestry and 2% with commodity-driven agriculture. At the sub-national level, Willcock *et al* (2016) found the majority of deforestation in Tanzania's Eastern Arc Mountains, was due to conversion to croplands. A recent pan-tropical study, found that small-scale cropland was the dominant deforestation driver in many African countries including Tanzania (De Sy *et al* 2019).

Despite this previous work, quantitative data on the relative contribution of different deforestation drivers at the national-scale in Tanzania, is considered inadequate for policy formulation. In the forestry sector, Tanzania's National Forest Policy (URT 1998) and the National Strategy for Reduced Emissions from Deforestation and forest Degradation (REDD) (URT 2013a), provide only nominal information on proximate deforestation drivers. The National Forest Policy cites '*agriculture, overgrazing, wildfires and charcoal production*' as the main drivers of deforestation, while the National REDD strategy notes the absence of data on the relative importance of deforestation drivers in the country.

Although charcoal production is considered to be a driver of forest degradation rather than deforestation in global studies (Curtis *et al* 2018), policy-makers firmly believe that charcoal production is a major driver of deforestation, in Tanzania (Mwampamba *et al* 2013). For example, the National Energy Policy 2015 sets an explicit objective of removing charcoal from the energy mix, with a view to reducing deforestation (URT 2015). In contrast, outside of the 38% of terrestrial land in PA, there is no clear policy to reduce the conversion of forest land to agricultural land (UNEP-WCMC and IUCN 2019).

Here we present the first national, empirical study of the proximate drivers of deforestation for Tanzania based on a combination of remote sensing, ground surveys and interviews. The objectives of the study were to assess the mix of drivers present in land deforested between 2010 and 2017. Specifically, we aim to inform ongoing policy discussions around the role of charcoal in deforestation (Doggart and Meshack 2017). We therefore include a range of drivers that are typically associated with forest degradation, with a view to improving our understanding of the interplay between drivers of deforestation and forest degradation at deforestation events in multiple land-use areas of Africa. By combining ground surveys and interviews with remote sensing, we provide a level of detail about the land use dynamics occurring in areas of deforestation, that cannot be captured using remote sensing alone, thereby complementing pan-tropical studies (Curtis *et al* 2018, De Sy *et al* 2019). Although our study is focused on Tanzania, the approach and findings have relevance to other countries, particularly to the other 18 early-transition countries in Africa (Hosonuma *et al* 2012).

2. Methods

Drivers were identified by combining analysis of satellite images, ground surveys, and informant interviews. Remote sensing was used to map areas of tree cover loss between 2010 and 2017. We assume that these areas are deforested, though tree cover may return in the future. Ground survey points were selected randomly from these deforested areas in an approach similar to the FAO Forest Resources Assessment dataset used by Gibbs *et al* (2010). For each ground survey point, we recorded the presence of different proximate drivers, the current land-use and a profile of the people involved in the deforestation. We recorded information on both deforestation and forest degradation drivers. The role of forest degradation drivers at deforestation sites was particularly relevant to this study given the policy-linked questions surrounding the relative contributions of charcoal and agriculture in driving deforestation, and a more widespread paucity of data on the co-occurrence of drivers of forest cover change (Mwampamba *et al* 2018). We also recorded signs of fire. Additional details on methods are provided in the supplementary materials, available online at stacks.iop.org/ERL/15/034028/mmedia.

2.1. Remote sensing

We used the freely available Global PALSAR-2/PALSAR/JERS-1 Mosaic product (Shimada *et al* 2014) together with the National Forest Resources Monitoring and Assessment of the Tanzania Mainland (NAFORMA) Land-use/Land-cover (LULC) Map 2010 (MNRT 2015) to map forest cover for all of the Tanzania mainland in 2010 and gross deforestation from 2010 to 2017. Forest was identified according to the Tanzanian definition submitted to the UNFCCC—areas of at least 0.5 ha with greater than 10% canopy cover of trees at least 3 m in height. Woodlands comprise ~93% of Tanzania's forest land cover of which ~81% is open woodland (10%–40% canopy cover) and 19% is closed woodland (>40% canopy cover) (URT 2017). We chose to base the deforestation analysis on L-Band Synthetic Aperture Radar (SAR) data, rather than optical sensor data such as Landsat (e.g. Hansen *et al* 2013) because of the well-documented advantages of L-Band SAR in detecting deforestation in African woodlands (Naidoo *et al* 2016, Bouvet *et al* 2018, McNicol *et al* 2018). The 2010 forest areas were mapped as areas not falling in wetlands, water, or flooded cropland in the 2010 NAFORMA LULC map, and having a minimum horizontal transmitting, vertical receiving (HV) backscatter digital number (DN) value of at least 2100 in 2007–2010 PALSAR data. Different thresholds were applied to identify the cut-off between forest and non-forest, with DN value $\geqslant 2100$ resulting in the most accurate forest map for the country. Deforestation from 2010 to 2017 was then mapped based on four criteria. The area had to be mapped as forest in 2010, have an HV backscatter DN value below 2100 in 2015, 2016, or 2017, show a relative decline in HV backscatter of at least 15% compared to the lowest HV backscatter value between 2007 and 2010, and be orthogonally connected to at least 5 other pixels of deforestation equivalent to 0.375 ha. We adopted a 6-pixel threshold for deforestation to maximise user accuracy whilst still being able to detect small-scale deforestation events. The accuracy of each of the map classes (non-forest, forest persistence, and deforestation) was assessed by visually reviewing Landsat, Sentinel-2, and Google Earth imagery for a random stratified sample of 300 pixels in each map class. A stratified sample was used in order to increase the sample size of the deforestation samples, since it was a rare class and the focus of the study. An independent assessment of roughly 100 points from each map class was conducted with 98% agreement between the two assessments. The accuracy assessment followed that described in Olofsson *et al* (2013, 2014), where the error matrix is presented as estimates of area proportions, in order to account for the stratified sampling design. The accuracy results and error matrix are presented in supplementary table S.1. Canopy height was considered in the accuracy assessment, alongside other criteria, where high resolution imagery allowed canopy height to be estimated.

2.2. Ground survey

To generate the ground survey points, we selected a random sample of 120 pixels from the deforestation map class. The map of deforestation and of the ground survey points are shown in figure 1. The accuracy of the 120 pixels was assessed visually using Landsat, Sentinel-2 and Google Earth imagery to confirm that the area was forest in 2009 or 2010 and non-forest in 2015, 2016 or 2017. Pixels that were inaccurately classified as deforestation were replaced with new random draws. Thirteen pixels were replaced once, and 1 pixel was replaced twice. This was within the margin of error for the reference data area, for the deforestation class (table S.2).

A survey team visited all the ground survey points. At each survey point, two plots were established centred on the deforestation pixel. A smaller plot (25 m $\times$ 25 m) was used to assess the current land-cover/land-use, including percentage tree cover, vegetation height and type, and to look for visible signs of drivers and fire. A larger plot (75 m $\times$ 75 m) was used to look for physical evidence of charcoal, grazing, and fire. Both plots were assessed by walking transect lines spaced 12.5 m apart running through the plots and along the sides. 360° panorama photographs were taken of each plot. At least one local government official accompanied the team to 95% of the survey points including all points in reserved land ($n = 15$), 78% of points on general land ($n = 9$) and 96% of points on village land ($n = 95$). In addition, village council representatives were present at 81% of the survey sites, including 95% of the points on village land. The survey was designed to describe the frequency with which different drivers occur at the national scale, rather than detecting spatial variations across the country.

2.3. Informant interviews

For each ground survey point a questionnaire survey with a local person was completed. Where possible, the current occupier or land owner was interviewed (15% of interviews). Where the owner/occupier was unavailable, a village council representative or other knowledgeable person was interviewed (63% of interviews), or in the case of land in PA, the PA manager (10% of interviews). The interviews were carried out in, or close to, the ground survey point. In this way the interview could use signs of land use in the plot, such

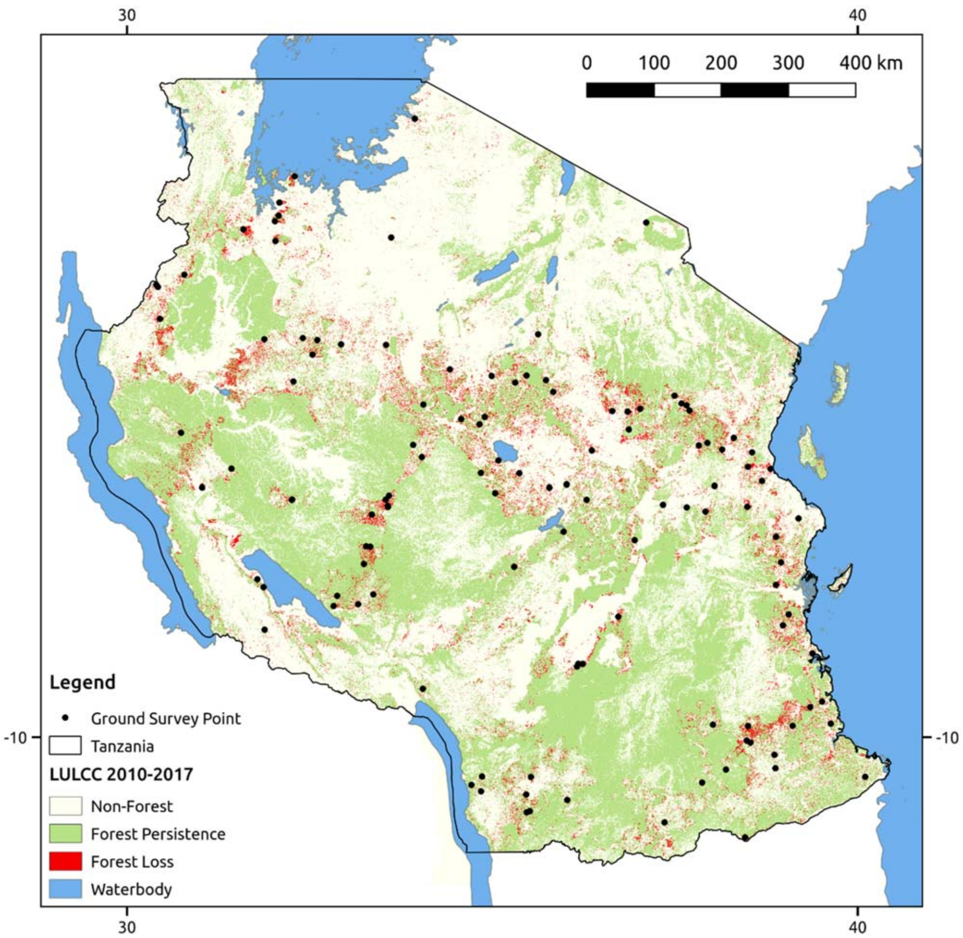

Figure 1. Map of forest loss in Tanzania during 2010–2017 and location of ground survey points.

as crop residues or signs of grazing, as prompts over the course of the interview.

2.4. Policy analysis

We updated Doggart and Meshack (2017) by reviewing the latest drafts of the National Environment Policy and the National Forest Policy.

3. Results

The gross annual deforestation rate was calculated as 561 704 $\pm$ 99 234 ha yr^{-1} or 1.42%, with a 2010–17 area of forest persistence of 37.7 Mha and an area of forest loss of 3.9 Mha, using the reference data area estimates.

Crop farming was the most frequently recorded driver of deforestation and was present in 89% of plots (figure 2(a)). Other frequently recorded drivers included livestock (69%), domestic fuelwood collection (41%), charcoal production (35%) and harvesting building poles (30%). Plantation forestry, roads, settlements, fuelwood collection for tobacco drying, and timber harvesting were each recorded in $\leqslant$6% of plots. Mining was not recorded as a deforestation driver in any plot. Signs of fire were present in 77% of plots.

Respondents stated that the primary reason for deforestation was 'to create a farm' in 81% of plots, all of which had signs of crop cultivation (figure 2(a)), while charcoal production was cited as being the main reason in 12% of plots, all of which had signs of charcoal production. 'Creating a farm' was cited by informants as being the main reason for deforestation in 67% of plots where charcoal production was recorded (n = 42) suggesting that most charcoal production occurs as part of a forest to crop land-use change trajectory. Harvesting timber in a pine plantation and livestock were both cited as the main reason for deforestation in 1% of plots, while respondents were uncertain of the main reason in 5% of plots.

The diversity of drivers per plot ranged from 1 to 6 (mean = 3.2. StDev = 1.4) (figure 2(b)). A single deforestation driver was recorded in 17% of plots. There were 30 different combinations of proximate drivers. The most frequent driver combination was crops-livestock (20% of plots), followed by a crops-only class (13% of plots). Charcoal was recorded most frequently in a crops-livestock-charcoal combination (8% of plots). Charcoal was not recorded as the sole driver in any plot.

Twenty-one crop types were recorded at the deforestation sites either through interviews or

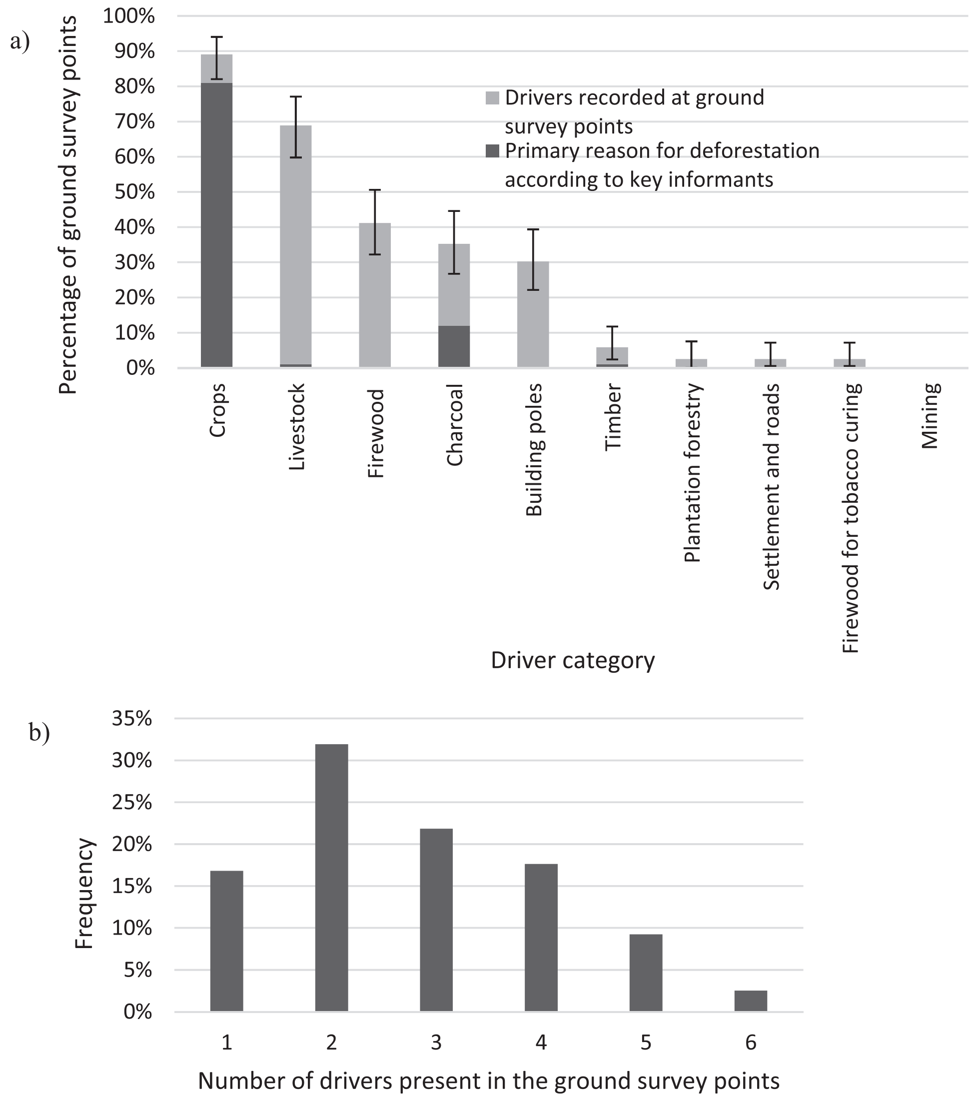

Figure 2. Prevalence of different drivers at the deforestation events included in the survey: (a) prevalence of different drivers with error bars showing the 95% confidence interval and the primary reason for deforestation according to key informants; (b) frequency distribution showing the number of drivers present.

observations, with 48% of all plots containing more than one type of crop (supplementary data table 2). The most commonly grown crops, as a percentage of all plots, were maize (57%), sesame (20%), cowpea (14%), and sorghum (10%). Other crops recorded in <10% of plots include rice, bean, cassava, sunflower, millet, cashew nut and ground nut. Crops were being grown both for subsistence and cash income. Of the 106 plots where agriculture was recorded, 47% were being farmed for both food and cash, 30% for food only, 12% for cash only and 10% were classified as unknown. Of those plots cleared for maize cultivation, 60% were for food and cash, 38% for food only and 1.7% were for cash only. The results point to the prevalence of small-scale mixed agriculture producing food crops for household consumption, often alongside cash crops.

The plots fell in fields at different stages of the agricultural cycle. 68% of plots were actively being farmed while 32% of plots were under fallow. According to respondents, the mean fallow period was 2.7 years (mode = 1 year), ranging from 1 to 8 years. Other studies have recorded average fallow periods of 3–4 years in Tanzania's Morogoro Region (Luoga *et al* 2000, Kilawe *et al* 2018) as well as evidence of shortening fallows and a shift to permanent cultivation in Tanzania (Grogan *et al* 2013, Kilawe *et al* 2018) and elsewhere in Africa (Zaehringer *et al* 2016).

The land-cover trajectory of the plots varied according to the driver. 21% of survey points, cleared primarily for charcoal production, had regenerated back into a forest class by 2018 while only 7% of those cleared primarily for agriculture had returned to forest. Several Tanzanian woodland tree species regenerate vigorously through coppicing (Sangeda and Maleko 2018). Ground survey points could have been regenerating for up to 4 years between 2015 and 2018 given the deforestation definition that required sample points to be non-forest in one or more of the years of 2015–2017.

Information about the residency of the people who originally cleared the forest, was available for 49 plots. In 67% of these plots, the forest was said to have been cleared by people who were not born in the village but had lived in the village for, on average, 8.7 years. The most frequently cited reasons for people to have moved to the area were: to secure better farming land (70% of responses) and to pursue economic opportunities (36% of responses). In most cases (58%), the farmers who were farming the land at the time of the survey were the same people who had cleared the forest. Responses about the gender of those involved in clearing the farms were provided for 50 farms, of which 30 were said to have been cleared jointly by women and men; and 20 were said to have been cleared by men only.

4. Discussion and conclusion

4.1. Quantifying the contribution of proximate drivers to deforestation in Tanzania

Our study demonstrates the primacy of agriculture in driving deforestation, confirming Tanzania-specific results from pan-tropical studies (Curtis *et al* 2018). We identify the main deforestation driver in each of our plots, on the basis of the 'main driver' identified during the informant interviews. Based on this, we attribute the proportion of deforestation to each driver as: agriculture (81%), charcoal (12%), livestock grazing (1%), plantation forestry (1%), and unknown/no clear main driver (5%). Overall our findings indicate that small-scale cultivation of maize, sesame, cowpeas and sorghum are the main proximate drivers of deforestation, predominantly for household consumption or local markets, with export crops contributing only marginally. While charcoal production was the primary reason for deforestation in 12% of plots, in over half of those plots, the land was then used for farming. We found no evidence of charcoal causing deforestation in isolation of other drivers. This confirms that charcoal is rarely a driver of deforestation on its own. Policies targeting charcoal in isolation of agriculture, are unlikely to be effective in reducing deforestation.

The typical deforestation scenario that emerges from the study, is a trajectory from forest land to agricultural land, predominantly (64% of agricultural areas) for maize cultivation usually in combination with one or more additional crops (80% of maize fields had one or more additional crop). In 33% of the agriculture-driven events, charcoal is produced as part of the transition process while livestock grazing, domestic firewood collection and timber harvesting were present in 66%, 42% and 7% respectively of the deforestation events involving agricultural crops. Less commonly (8% of all ground survey points), charcoal is produced outside of a transition from forest to crop cultivation. In such cases, charcoal is always found to co-occur with livestock grazing. Rarer events include 1% of events that only involved livestock grazing.

Our results comprise new evidence that multiple drivers of deforestation and degradation frequently co-occur in areas of deforestation. Whilst the convergence of multiple drivers is recognised by other studies (Geist and Lambin 2002), most previous studies have focused on the main drivers (Hosonuma *et al* 2012). Co-occurrence of drivers will affect the ecological and climate forcing impacts of deforestation events and will require different policy responses (Mwampamba *et al* 2018). The implications of co-occurring drivers of forest change are poorly understood and require further research.

4.2. The role of subsistence versus commercial crops and livestock in deforestation

In terms of agriculture's role in deforestation, our study provides new evidence around the relative contribution of different crops to deforestation, with relevance to agricultural policy. The dichotomies of 'subsistence/commercial' and 'shifting/commodity-driven' agriculture as applied by Hosonuma *et al* (2012) and Curtis *et al* (2018) are difficult to apply in the Tanzanian context. If we consider those distinctions to comprise a continuum rather than a dichotomy, with production for household consumption at one end, and production for commodity export at the other end, then most Tanzanian agriculture remains closer to the 'subsistence' end. In terms of crops present in areas of deforestation, Hosonuma *et al* (2012) describe a shift from subsistence to commercial crops, as countries shift from early to late-transition phases. We found that four crops occurred in deforestation events at least twice as frequently as their overall prevalence in Tanzania: maize, sesame, cowpeas and sorghum (supplementary data table 3) (FAOSTAT 2019). For example, maize is the most widely cultivated crop in the country covering 24% of crop land in Tanzania, but occurred in 64% of agriculture-driven deforestation events. Other crops such as rice, beans, cassava, sunflower, groundnut, cashew nut and millet were recorded in roughly the same proportion of plots, as they comprise of the overall agricultural estate. Of the four crops most frequently detected in deforestation events, sesame is the crop that is most frequently exported, with 18% of production being exported (*ibid*). Tanzania's main export cash crops (excluding cereals) are tobacco, cashew nut, coffee, tea, clove and groundnut. Of these export crops, cashew nut, groundnut and tobacco were the most frequently recorded in 4.2%, 3.4%, and 0.9% respectively, of all plots. Tea, coffee and clove were not recorded. These findings reinforce the conclusion that deforestation, in Tanzania, is largely driven by small-scale, predominantly subsistence agriculture.

4.3. The role of drivers of forest degradation in deforestation events

Our findings suggest that livestock grazing may play a more significant role in driving deforestation than previously considered. Livestock grazing was identified as the primary reason for deforestation in only 1% of plots, but was recorded in 69% of plots. Livestock grazing was recorded in 92% of the plots where crop cultivation was not recorded, 66% of plots where crops were reported and 83% of events where charcoal was recorded. The number of cattle in Tanzania increased by 4% p.a. between 2010–17 (FAOSTAT 2019), suggesting that the impact of livestock grazing may be increasing. The conditions under which livestock grazing acts as a driver of deforestation or of forest degradation requires further research, a conclusion also reached by Mwampamba *et al* (2018).

Fire is an important tool in rural livelihoods, being used by farmers to clear vegetation in preparation for planting crops, by hunters to flush out prey, by livestock keepers to stimulate fresh grass for grazing, as well as for cultural reasons (Katani *et al* 2014). The study provides new evidence on the extent of fire use in land management in Tanzania. We found a particularly close association between fire and agriculture: fire was recorded in 80% of plots involving conversion of forest land to crop land, compared with only 53% of plots where no signs of agriculture were recorded. Fire was not observed in some areas under cultivation. This may be because signs of burning had been masked by subsequent crop cultivation, and as such, our results may under-estimate the prevalence of fire.

Although the study was not designed to detect differences in the distribution of drivers across the country, we noted that livestock and agriculture were detected in points widely distributed across the country, while charcoal was only consistently absent from the ground survey points south of the Rufiji delta and east of the Selous Game Reserve. This observation should be treated with caution as the authors are aware that charcoal is produced in this area. Further research is needed to detect sub-national spatial patterns in the distribution of drivers.

While there is growing recognition of the significance of forest degradation in global change accounting (Goetz *et al* 2015, Baccini *et al* 2017, Song *et al* 2018), forest degradation was not the focus of the current study and is an area requiring further research. Africa's open woodlands, where tree cover is naturally only 10%–40%, present specific issues around definitions of deforestation and forest degradation. Canopy cover thresholds determine both the extent of land defined as forest and the extent of deforestation. Recovery of canopy cover after forest loss is often very rapid resulting in a fast dynamic between canopy loss and recovery (McNicol *et al* 2018), further blurring the distinction between deforestation and forest degradation. This dynamic matters because the climate impact of deforestation or forest degradation will depend on the land-use trajectory with implications both for climate modelling and for policy (Tongwane and Moeletsi 2018, De Sy *et al* 2019).

4.4. Policy implications

In the absence of empirical data on deforestation drivers at the national scale in Tanzania, policy efforts have focused on reducing charcoal production. Conversion of forests to agricultural land outside of PA has received limited attention and a coordinated policy to reduce deforestation, across energy, agriculture and forestry sectors is lacking. In the energy sector, the National Energy Policy (URT 2015) seeks a transition from woodfuels to electricity and fossil fuels, citing deforestation as a rationale for the shift. There have also been periodic bans on the charcoal trade (World Bank 2009, Zulu and Richardson 2013). Discussions around a charcoal strategy or policy have been ongoing for more than a decade (Doggart and Meshack 2017). Policy implementation tools in the forestry sector have focused on tree planting as an alternative to natural forests for woodfuel biomass, with ambitious targets for the expansion of tree plantations. In contrast, policy implementation tools have not set targets to reduce conversion of natural forests on village land, to agriculture. Community-based forest management (CBFM) is the forestry sector policy tool designed to protect forests on village land, however, CBFM has received minimal support, beyond donor and Non-Governmental Organisation interventions.

In the agriculture sector, the National Agriculture Policy 2013 has a mission of, '*increased volumes of competitive crop products*' to be achieved through a combination of intensification and the expansion of agricultural land. The policy states that '*Whereas 44 million hectares of land are suitable for agricultural production, only 10.8 million hectares (24%) are cultivated… The potential exists for expansion of agricultural area under cultivation.*' The policy states that, '*the ministry responsible for Natural Resources shall support sustainable management of forest resources especially through Participatory Forest Management*'. (URT 2013b.) With this statement, the agriculture policy, deflects responsibility for addressing agriculture-driven deforestation to the neglected policy tool of participatory forest management. Many authors agree that sustainable intensification of agriculture can play an important role in reducing deforestation provided that a deliberate commitment to protecting forests runs alongside the shift in agricultural practices (Ngoma *et al* 2018, Balmford *et al* 2018). This highlights the importance of inter-sectoral cooperation.

Although Tanzania's policies in land, agriculture, environment, water, energy and forests, recognise the benefits of protecting forests, a more coordinated and deliberate policy is needed to balance the protection of forests and the ecosystem services that they provide, with strategies to achieve increased production of crops and livestock. The current emphasis on controlling trade in charcoal and timber is unlikely to be effective, as a strategy to reduce deforestation, but could reduce forest degradation, particularly where compliance efforts target PA. Achieving a more coordinated policy response requires a clearer national vision around the allocation of land and a shift towards more inter-sectoral cooperation in addressing the multiple drivers of deforestation and forest degradation. Without a deliberate policy shift, there is a risk that Tanzania will follow the trajectory followed by so many other countries towards a natural forest cover of only 15%, with concomitant losses of Tanzania's unique biodiversity and other ecosystem services.

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Data availability statement

The data that support the findings of this study are openly available in the supplementary material and at https://doi.org/10.25412/iop.11395185.v1.

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Chapter 4 Agricultural fallows are the main driver of natural forest regeneration in Tanzania

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Agricultural fallows are the main driver of natural forest regeneration in Tanzania

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Abstract

Rates and drivers of natural forest regeneration are areas of uncertainty for policy, forest management and climate change mitigation. In this study, the rate of deforestation and the rate and drivers of natural regeneration are described for 56 million hectares of village land in Tanzania, a country undergoing rapid deforestation. To determine the regeneration and deforestation rates, remote sensing (RS) data for 500 randomly selected points were reviewed for a 34 year period from 1987 to 2021 using Google Earth Engine. Over this period, regeneration, involving a transition from forest to non-forest and back to forest was detected on 4.8% of village land (95% CI: 3.1%–7.1%), while 0.8% of land transitioned from non-forest to forest (95% CI: 0.2%–2.04%). 22% of village land was deforested (95% CI: 18.6%–26.1%), equivalent to a mean annual net loss of 0.35 million hectares of forest. Using a combination of RS data, field plots and structured interviews, the land cover change trajectories of 180 regenerating plots, in 10 sampling clusters, were assessed to identify regeneration drivers and assess biomass and tree species accumulation rates. Agricultural fallows are the regeneration driver in 47% of plots (95% CI: 39.8%–54.8%). Other common regeneration drivers include abandonment of cultivated areas for reasons apart from fallowing, conservation and post wood-extraction abandonment in 19% (95% CI: 13.9%–26%), 18.3% (95% CI: 13%–24.8%) and 12.8% (95% CI: 8.3%–18.6%) of plots, respectively. The mean carbon sequestration rate was 1.4 Mg C ha^{-1} y^{-1}, equivalent to 4.3 Tg C y^{-1} (95% CI: 3.9–4.7 Tg C y^{-1}) across the 3.15 million hectares of regenerating village land forest. The mean species accumulation rate was 1.08 species y^{-1} (95% CI: 1.0–1.2). Regeneration time, location and precipitation have the greatest influence on biomass and species richness. The study highlights the potential for natural regeneration to contribute to global and national climate and biodiversity goals and to sustainable, productive forest management. The importance of cooperation and policy-alignment between the forest, agriculture and land sectors are under-scored.

1. Introduction

Increasing forest area, through natural regeneration, can benefit climate, biodiversity and local livelihoods [1–3]. Globally, forest regrowth is estimated to sequester 1300 Tg C y^{-1} [4]. Regenerating forests, including forest fallows in shifting-agriculture, provide ecological services and products vital to the livelihoods and climate resilience of millions of people [5–7]. Natural regeneration is also integral to the Bonn Challenge goal of restoring 350 million hectares of land by 2030[6]. However, rates and drivers of natural forest regeneration are uncertain despite being important for forest policy, forest management and climate change mitigation, and have received less attention than rates and drivers of deforestation, particularly in Africa [8–10].

With ∼48 million hectares of forest [11], Tanzania is a country in the early transition phase of the forest transition model, a trajectory from deforestation to reforestation that has been observed in many countries [12, 13]. Typical of countries in the early transition phase, the deforestation rate is increasing, while the regeneration rate is uncertain. Estimated regeneration rates for Tanzania range widely from 5–8000 ha y^{-1} (1990–2010, 11) to 25 342 ha y^{-1} (2000–2012, 14). Tanzania's forest reference emission level (FREL) excluded consideration of forest re-growth due to insufficient data [15].

There is also uncertainty on biomass increment rates in regenerating African forests with reported average rates for miombo and *Acacia* woodlands ranging from 1.2 Mg ha^{-1} y^{-1} to 4.2 Mg ha^{-1} y^{-1} over the first 14–35 years of re-growth [16–18]. Biomass accumulation rates are used to quantify the role of forests as carbon sinks [19] and to set sustainable harvesting rates [20], including for charcoal [21, 22], an important energy source across Africa [23]. While biomass accumulation rates are known to be affected by biophysical factors, land use history and connectivity [18, 24], there is also uncertainty around the relative influence of factors that trigger, enhance or inhibit regeneration [9, 25, 26].

With a focus on village land, in Tanzania, the study objectives are:

1. To assess the natural forest regeneration rate;
2. To assess the relative contribution of regeneration drivers;
3. To determine biomass and species accumulation rates, and their determinants, in naturally regenerating forests; and
4. To estimate carbon sequestration and sustainable harvesting rates in naturally regenerating forests.

2. Definitions, study area and methods

Figure 1 summarises the study's workflow.

2.1. Definitions

For this study, forest is defined as an area of ⩾0.5 ha with ⩾10% canopy cover of trees ⩾3 m in height [15]. Natural regeneration is defined as a change in land cover from non-forest to forest, in an area that was historically forest, through natural growth, excluding anthropogenic tree-planting (based on [27]). Conversely, deforestation is defined as a change in land cover from forest to non-forest [28]. The regeneration rate describes the proportion of land covered in naturally regenerating forest. The regeneration rate is a sample-based estimate derived from remote sensing (RS) data. Regeneration drivers are the triggers that directly result in the conversion of land from non-forest to natural forest. Often, this will be the cessation of an activity such as cultivation. Regeneration drivers often comprise an absence of human activity, in contrast to the presence of human activities that characterise most deforestation drivers [29]. Underlying the direct regeneration drivers, are complex, multi-scale interactions between economic, policy, demographic and biophysical influences [30].

2.2. Study area

The study area is village land in mainland Tanzania (figure 2(a)). Village land is legally defined as '*land, other than reserved land, which the villagers have…been regularly occupying and using … including land lying fallow*' [31]. As there is no published map of village land, it was mapped as a residual class excluding government-owned protected areas (including all mangrove forest) and plantations, urban areas, and private estates. The village land map was overlain onto the land use/land cover map prepared by the National Forest Resources Monitoring and Assessment of Tanzania [11]. The map is mainly derived from Landsat data and uses a vegetation classification system compatible with the FAO Global Forest Resources Assessment. Vegetation types include lowland deciduous forest, woodland, bushland and thicket [11]. Village land classified as grassland (3.2 Mha) or lowland and montane forest (0.6 Mha) by [11] were excluded as being inappropriate for sustainable forest-product harvesting (Objective 4). The study area covers 56 295 277 ha, 61% of mainland Tanzania.

2.3. Land cover change trajectories

Using Google Earth Engine (GEE) [32], land cover change trajectories of 500 15 m radius, randomly located points were reviewed visually, based on 1987–2021 data from Landsat 5, 7 & 8, PALSAR 1 & 2 and Sentinel 2 (figure 2(a)). High-resolution images from Google Earth Pro were also used. For each year that one or more images were available per remote sensing sample point (RSSP), land cover was classified using standardised land cover classes such as forest, woodland, bushland and agriculture (S1.1). Three assessors carried out independent analyses of a subset of RSSPs, followed by a joint review, until reaching 90% consistency [33]. RSSPs were classified into one of 21 land cover change trajectory classes

[6] https://www.bonnchallenge.org/about.

Step 1. Map the village land study area.

Step 2. Randomly select 500 15-metre radius points and classify the 1987–2021 land cover change trajectory, for each point.

Step 3. Use the first 10 points to be identified as regeneration (Step 2), to select 10 sampling clusters.

Step 4. Visually identify 19 additional field survey sample plots per cluster.

Step 5. Vegetation plots and structured interviews at each field survey sample plot.

Step 6. Determine regeneration time based on remote sensing and interview results.

Step 7. Calculate biomass and species richness per plot and compare with regeneration time and other variables.

Figure 1. An overview of the workflow of the study.

and, where applicable, the year(s) when deforestation events and/or the first indication of regeneration occurred, were documented. The median starting year for the analysis was 1987. A 1987 Landsat 5 image was available for 49% of RSSPs. On average, for each RSSP, there was one or more usable image for 26 of the years between 1987 and 2021 (Range: 14–34 years). Confidence intervals were calculated in r using the binom.test tool.

2.4. Field survey sampling strategy

For the field survey, a clustered sampling strategy was applied with ten clusters in separate administrative districts (figures 3(a), S1.11). Clustered sampling has been widely used in forest biomass research [34]. The first ten RSSPs to be classified as regeneration from Step 2 (figure 1), were used to identify the sampling clusters (Step 3). This provides a random sampling basis for the identification of the clusters. For each cluster, 19 additional points of natural regeneration were selected by visually reviewing the land surrounding the original RSSP (Step 4). The land cover change trajectory of each field survey sample plot (FSSP) was documented from 1987 to 2021 using the GEE datasets [35]. For each sampling cluster the study area was limited to land within ±150 m in elevation, relative to the original sample point. FSSPs were selected as close as possible to the original point with at least 25 m between FSSPs. The field survey was carried out between 4 October 2021 and 23 November 2021, before the rainy season.

2.5. Vegetation plots

Each FSSP is a 0.07 ha 15 m horizontal radius circular plot. Plot centre coordinates were recorded using handheld Garmin 64s GPS units. The diameter breast height (dbh) and species were recorded for all stems >5 cm. Stump diameter was measured at 30 cm or, if height was <30 cm, the top height and diameter. All trees with <5 cm dbh and ⩾135 cm height, were measured in a 1 m horizontal radius sub-plot at the centre of the main plot. Data was recorded on mobile phones using the Open Data Kit (ODK) tool [36] and uploaded as network allowed. The method is based on Tanzania's national forest inventory protocols [37]. Horizontal plot radius was adjusted for slope in the field. 360° photographs were taken of each plot. Observations of canopy cover and height, and land use were documented with additional information on features of interest.

2.6. Structured interviews (SIs)

At each FSSP, people knowledgeable about the local area were interviewed ($\bar{x} = 3$ informants/FSSP; range: 1–5). The 642 interviewees included district and/or village government representatives at 80% of FSSPs. Where possible, the landowner (29% of FSSPs) was interviewed. In 58% of FSSPs, one or more person considered themselves to be 'very familiar' with the

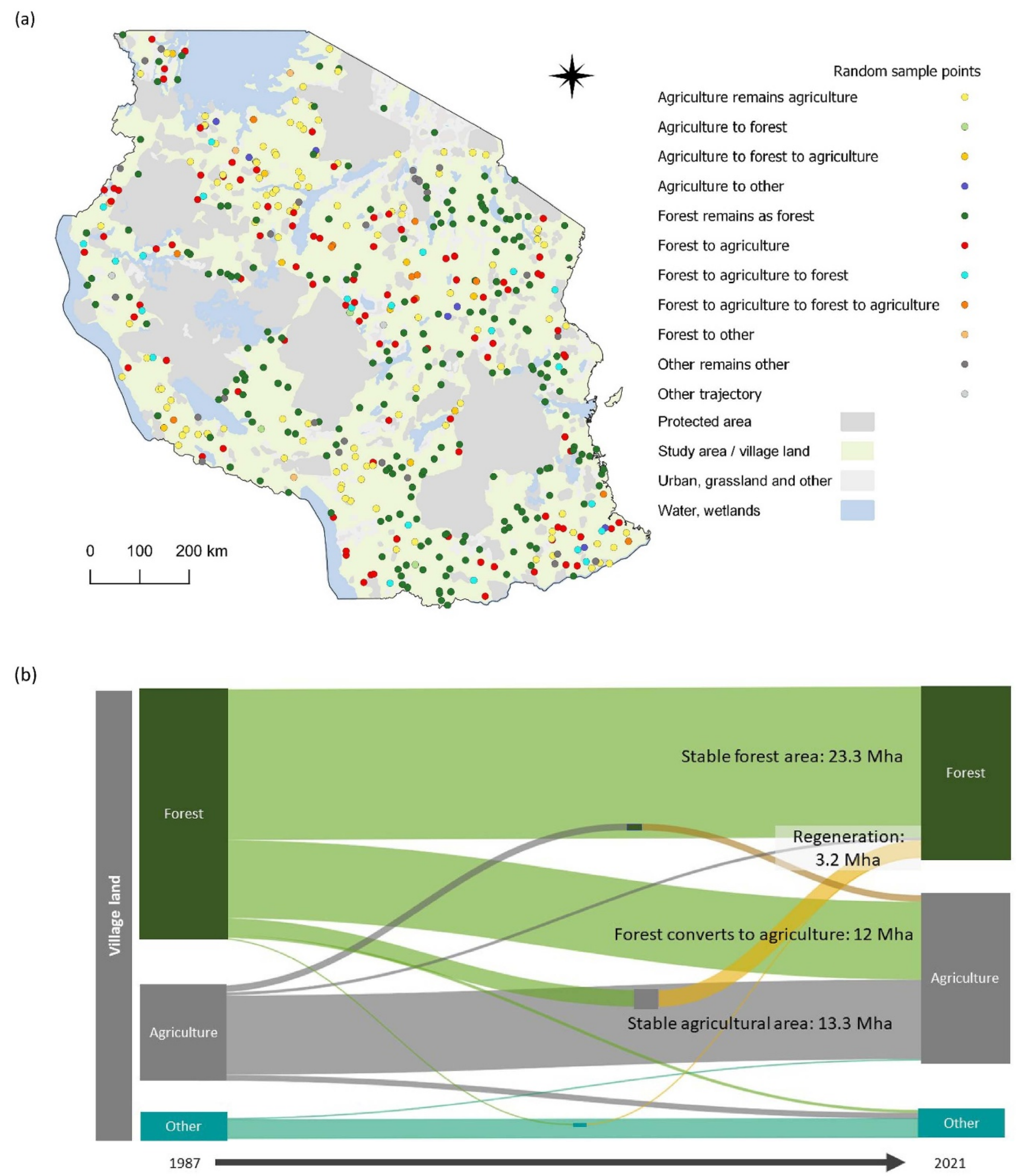

Figure 2. Land cover change trajectory results. (a) Map of land cover change trajectories for 500 randomly selected remote sensing sample points across village land in mainland Tanzania; and (b) Sankey chart showing land cover change transition on village land in Tanzania from 1987 to 2021. The width of the flows is proportional to the area of land transitioning between classes. For land that transitions, once or more, through an intermediary class (e.g. forest or agriculture), the transitioning flow overlaps the stable flow for the intermediary class, such as the regeneration flow's midway overlap with the stable agriculture flow. The timing of land cover change varies between sample points and is not to scale in the chart. 'Other' includes areas of settlement, road, grassland and wetland. See S1.1 for detailed class descriptions. Made with SankeyMATIC https://sankeymatic.com/.

land. The SIs were carried out in, or close to, the FSSP. Interviews were conducted in Swahili. Responses were recorded on ODK forms, available in Swahili and English.

Interviews covered the land use/cover history of the plot, including questions on cultivation, livestock, charcoal, tree-cutting for timber, fuelwood and building-materials, fire, wildlife-herbivory and physical events such as floods and landslides (S1.5).

2.7. Calculating stand parameters

2.7.1. Vegetation type

Plots were classified into four vegetation types, based on species composition: *Acacia-Commiphora* bushland, Itigi bushland-thicket, lowland deciduous forest and miombo woodland (MW) [37].

2.7.2. Height

Tree-height (H) was estimated for all stems, for the bushland and lowland forest classes, using

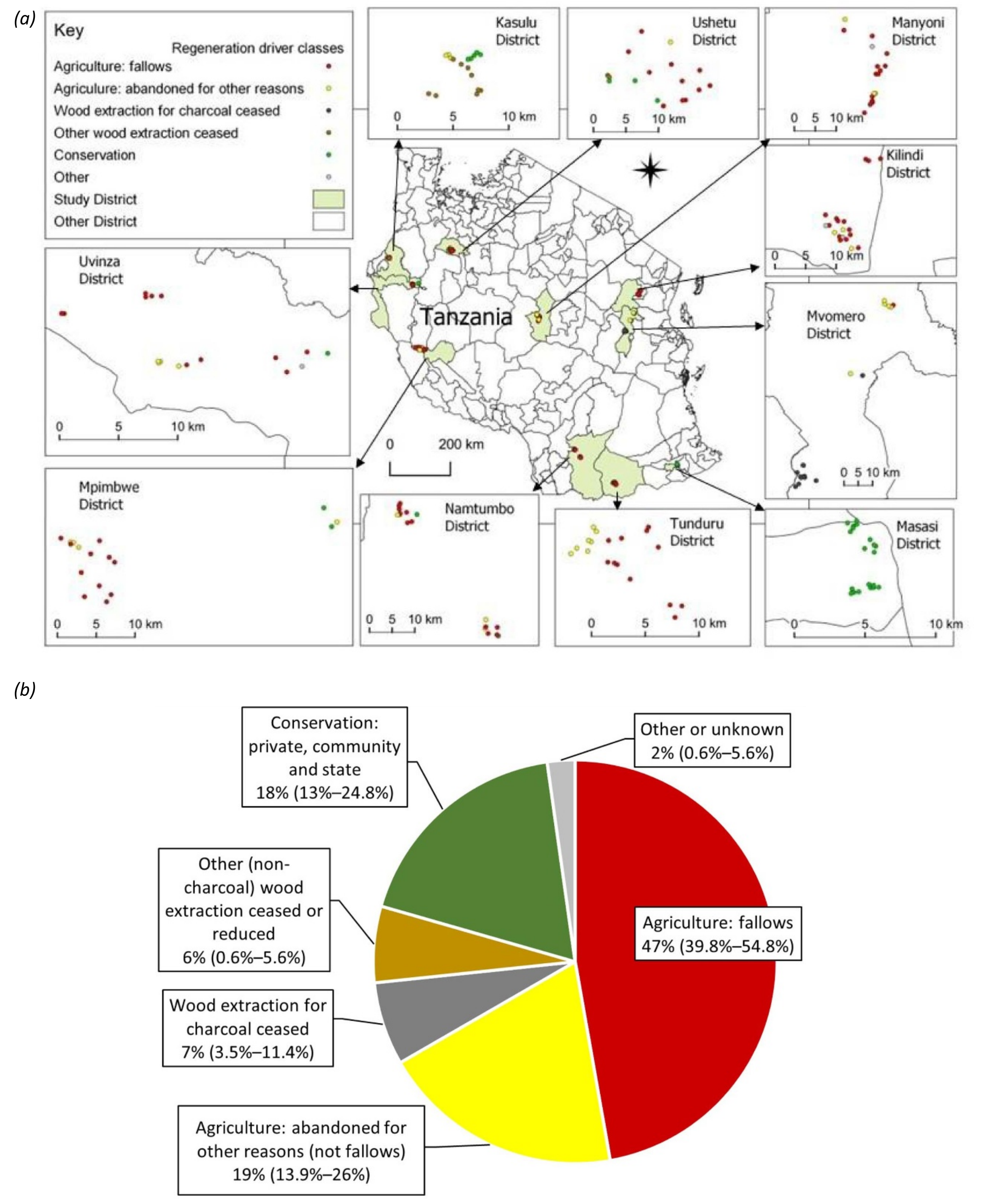

Figure 3. Distribution and frequency of regeneration drivers (a) Map of field survey sample points showing main regeneration driver at each point; (b) frequency of regeneration drivers (95% confidence interval).

equations (1) and (2), respectively. Height was not measured for all trees but is a required variable for the optimal biomass models for bushland and lowland forest [38].

Equation 1 *Diameter to height model for Acacia-Commiphora bushland* [39]

$$\boldsymbol{H} = 1.3 + 37.0396 \times \left(1 - \exp\left(-0.03778 \times \boldsymbol{D}^{0.6063}\right)\right). \quad (1)$$

Equation 2 *Diameter to height model for lowland forest* [39]

$$\boldsymbol{H} = 1.3 + 24.9862 \times \left(1 - \exp\left(-0.0579 \times \boldsymbol{D}^{0.7862}\right)\right). \quad (2)$$

2.7.3. Above ground biomass (AGB)

AGB (Y) values include alive and standing dead trees (>135 cm height). Biomass cleared during the preceding 3–4 years, based on stumps, is also included. AGB was calculated using the equations:

Equation 3 *Model to predict biomass for Acacia-Commiphora bushland [40]*

$$Y = 0.0292 \times D^{2.0647} \times H^{1.0146}. \quad (3)$$

Equation 4 *Model to predict biomass for bushland-thicket [41]*

$$Y = 1.2013 \times D^{1.5076}. \quad (4)$$

Equation 5 *Model to predict biomass for miombo woodland [42]*

$$Y = 0.1027 \times D^{2.479}. \quad (5)$$

Equation 6 *Model to predict biomass for lowland forest [38]*

$$\boldsymbol{Y} = 0.0873 \times \left(\boldsymbol{W} \times \boldsymbol{D}^2 \times \boldsymbol{H}\right)^{0.9458} \quad (6)$$

where Y = biomass (Mg); W = wood density (g cm^{-3}); D = diameter at breast height (cm); H = height (m).

Species-specific wood-density estimates were extracted from the BIOMASS package in R [43].

To exclude biomass that accumulated before the regeneration time, remnant biomass was calculated and deducted (S1.7), affecting 119 trees in 51 FSSPs out of a total of 9757 trees in the 180 FSSPs.

2.7.4. Tree species richness (SR)

Number of species of alive and dead trees and stumps in the sub-plot and main plot.

2.7.5. Stem density

Disaggregated count of alive and dead stems >135 cm height, and of stumps, extrapolated to a per hectare value.

Stand parameters were calculated in R [44].

2.8. Regeneration time

Regeneration time was determined using the RS data, the results of the SIs and field survey observations. Interviewees reported the year in which cultivation or other human activities last occurred. For the 167 points with both RS and SI regeneration starting years, 57% differed by ⩽5 years. The year in which regeneration was first detected using the RS data was usually later than the SI-reported year that cultivation, or another activity, stopped, likely reflecting the time taken for regeneration to be detectable using RS.

2.9. Random forest (RF) for regression

The influence of 10–11 variables (table 1) on AGB and SR was assessed using the RFs for Regression package [45]. Vegetation was only considered for the 'all plot' analysis. Number of trees was set to 601. Number of variables at each split used the default value of 1/3 of the number of variables. The variable 'District' was included as a proxy for other place-based influences. As only six points were in the Itigi bushland-thicket class, it was merged with the Acacia-Commiphora bushland class, for this analysis.

2.10. Carbon calculations

Total carbon stored in regenerating village land was calculated using equation (7).

Equation 7 *Model to calculate total carbon stored in regenerating forests on village land*

$$\boldsymbol{C} = \boldsymbol{Abxy} \quad (7)$$

where

C = total carbon in regenerating forest on village land (Tg)

A = village land area: 56 295 277 ha

b = % study area under regeneration: 5.6%, based on the study results, equal to 3 152 536 ha

x = mean AGB in FSSPs equal to 39.2 Mg ha^{-1}

y = biomass to carbon conversion factor: 0.47 [46].

3. Results and discussion

3.1. Regeneration and deforestation rates

Natural regeneration was detected on 5.6% (95% CI: 3.75%–7.99%) or 3.15 Mha of village land in 2021, of which 4.8% (95% CI: 3.1%–7.06%) and 0.8% (95% CI: 0.22%–2.04%) of points were forest and non-forest in 1987, respectively (figures 2(a) and (b)), comparable to rates in southern Tanzania (4%) and the Brazilian Amazon (∼4%) [47, 48]. This means that only 0.8% (0.45 Mha) of village land gained forest, when comparing land cover in 1987 and 2021, similar to the 0.34% recorded for 2000–2012 in Tanzania by [14]. In contrast, 21.4% (95% CI: 17.8%–25.26%) (12.05 Mha) of village land was converted from forest in 1987 to agriculture in 2021, with an additional 0.8% (95% CI: 0.22%–2.04%) (0.64 Mha) converted from forest to residential or other non-agricultural use. Regeneration, including long fallow, is a rare land class. Conversion of forest land to permanent agriculture is the dominant trend, supporting findings by other land cover change studies in the area [49, 50].

Overall, Tanzania experienced a *net* transfer of 21.4% (95% CI: 17.88%–25.26%) of village land from forest to non-forest, equivalent to 12.05 Mha. Since only 68.4% (95% CI: 64.12%–72.46%) or 38.5 Mha of village land was forest in 1987, the proportion of village land forest that has been converted to non-forest is higher, at 32.46% (95% CI: 27.52%–37.7%). Over the 34 year study period, this is equivalent to a mean net loss of 0.35 Mha y^{-1} or a mean gross loss of 0.37 Mha y^{-1}. This is lower than the 0.47 Mha y^{-1} gross deforestation rate for 2002–2013 reported in Tanzania's FREL [15]. This reflects the study's longer timescale and accelerating deforestation over this period. The median year that deforestation occurred was 2010 indicating more deforestation in the final decade of the study period than in the preceding two decades. Using data on the most recent year that each deforested point transitioned from forest to non-forest (figure 1. Step 2), 11% (95% CI: 8.22%–13.86%) (6.08 Mha) of village land transitioned from forest to non-forest between 2011 and 2021 equal to a village-land deforestation rate of 0.608 Mha y^{-1}. This also indicates that Tanzania's deforestation mostly occurs on village land, not in protected areas. Some land (6.8% (95% CI: 4.75%–9.37%)) fluctuated temporarily between classes before returning to its original class, including land that cycled once or twice from forest to agriculture and back to forest (4.6% (95% CI: 2.94%–6.82%)), or passed through one or two cycles of transitioning from agriculture to forest and back to agriculture (1.8% (95% CI: 0.83%–3.39%)). These fluctuations are overlooked by land cover change analyses that only compare land cover at the beginning and end of a study period [14]. The mean regeneration time for the RSSPs with regenerating forest was 10.9 y ($\sigma = 6.8$ y, range: 1–22 y, $n = 28$).

Regenerating forest is sparsely distributed in a band from east-central to west-central Tanzania, with a few points in the south-east (figure 2(a)), similar to [14]. Stable forest areas are abundant in the north-east and south, while stable agricultural areas are abundant in the south-west and north-west. Deforestation is highest along the coast and in an east-west swathe across central Tanzania, a pattern also detected by previous studies [11, 14, 49].

3.2. Regeneration drivers

Most regeneration is triggered by a cessation of cultivation, either for fallowing (47.2% of FSSPs (95% CI: 39.8%–54.8%)) or for other reasons such as labour shortage or poor soil (19.4% of FSSPs (95% CI: 13.9%–26.0%)) (figures 3(a) and (b)). That fallows are the most common regeneration driver indicates that shifting-cultivation continues to be practised in Tanzania, despite a regional decline [51, 52]. Fallows' dominance in Tanzania's forest regeneration dynamics, is also a product of applying IPCC deforestation and FAO regeneration definitions based on land cover, rather than land use. Where conservation is the main regeneration driver (18% of FSSPs (95% CI: 13.0%–24.8%)), forest was being conserved by private landowners including for beekeeping, communities as village land forest reserves and local government in an area of village land recently designated as a government forest reserve. Post-charcoal production regeneration (6.7% of FSSPs (95% CI: 3.5%–11.4%)) was found in only one district. The cessation of other wood extraction was also uncommon (6.1% of FSSPs (95% CI: 3.1%–10.7%), mostly recorded in Kasulu District following the closure of a refugee camp.

Data from 180 FSSPs, out of the original 200 FSSPs were used in the analysis. Detecting regeneration using RS datasets is challenging due to the long timescales, high variability and limitations of RS in distinguishing between early regeneration, crops, woodlots or agroforestry [53]. Type 1 errors occurred on five occasions where the points were identified as natural regeneration but were found to be cassava cultivation (4 points) and a woodlot (1 point). These points were replaced with nearby, alternative points. Fourteen FSSPs, cleared between the last GEE image and the survey team's arrival, are excluded from the analysis.

3.3. Above ground biomass

AGB varied from 3.9 Mg ha^{-1} to 134.4 Mg ha^{-1} ($\bar{x} = 39.2$ Mg ha^{-1} $\sigma = 22.7$ Mg ha^{-1}) (table 2). Including biomass accumulated prior to the regeneration period, maximum biomass was 180.9 Mg ha^{-1} ($\bar{x} = 42.4$ Mg ha^{-1} $\sigma = 25.6$ Mg ha^{-1}, $n = 180$). Compared with national average biomass values, the FSSP results are similar for MW, higher for bushland and lower for lowland forest, where national averages are 42.5 Mg ha^{-1} for open woodland; 19 Mg ha^{-1} for dense bushland and 92.9 Mg ha^{-1} for lowland forest (applying a 2.13 carbon to biomass conversion coefficient [46] to carbon values in [54]). This indicates that, on average, the AGB of regenerating bushland and woodland is at least as high as the national average, while lowland forest recovery is slower, comparable to results from Zambia [55] and the Congo Basin respectively [26, 56].

Previous studies, in East African woodlands, find that precipitation, vegetation type, regeneration time, human actions and wildlife affect AGB and SR in regenerating areas [24]. Based on the study's RF regression models, time, precipitation and location/district have the strongest influence on AGB, with vegetation type, fire, livestock and the deforestation driver, having a moderate overall influence (table 1, figures 5, S1.10). Livestock were most influential in lowland forest, exceeding the influence of regeneration time. Charcoal, tree-cutting, pre-regeneration cultivation and conservation had a negligible influence. AGB in the bushland class could not be explained by time (figure 4(a), table 1). The importance of time, disturbance type and fire is in line with other studies [5, 16].

The RF models that included stump biomass, but excluded remnant tree biomass, explained 37.6% of the variance, compared with only 26% and 22% of variance explained respectively when both remnant biomass and stumps were excluded, or both were included.

The mean biomass accumulation rate, calculated as biomass (excluding remnant tree biomass) over regeneration time, was 2.9 Mg ha^{-1} y^{-1} ($\sigma = 1.68$ Mg ha^{-1} y^{-1}, n = 180). It was lowest in bushland ($\bar{x} = 2.13$ Mg ha^{-1} y^{-1}, $\sigma = 1.78$ Mg ha^{-1} y^{-1}, $n = 43$) and highest in MW ($\bar{x} = 3.35$ Mg ha^{-1} y^{-1}, $\sigma = 1.29$ Mg ha^{-1} y^{-1}, $n = 86$). Other studies in MW report rates ranging from 1.2 Mg ha^{-1} y^{-1} [16] to 4.2 Mg ha^{-1} y^{-1} [55] in Zambia; and 1.4 Mg ha^{-1} y^{-1} in Mozambique [57]. In drier *Acacia* woodlands, a rate of 1.3 Mg ha^{-1} y^{-1} was recorded over a 14 year period, in Kenya [17] while in semi-deciduous forest in Ivory Coast the rate was higher at 4.23 Mg ha^{-1} y^{-1} [18].

Biomass accumulation rates were highest in the 5–10 year FSSPs and declined with age (figure 4(b)). This is earlier than records of 12–14 years for *Acacia* woodland [17], 18 years for MW [24] and

Table 1. Variable descriptions and random forest regression results for above-ground biomass and species richness.

Rank for influence on biomass	Variable	Mean accuracy decrease (%IncMSE): how much the RF model accuracy decreases, if we exclude the variable. Highest values per vegetation class are in bold — Above ground biomass: All	BA&BT	CL	MW	Species richness: All	BA&BT	CL	MW	Variable description	Data source	Number of plots in which the variable was present (% plots) or summary statistics (time, precipitation)
	All variables	34.1	19.9	39.4	31.0	63.4	20.9	42.8	52.9			
1	Time	**24.3**	−1.1	8.5	**37.9**	10.2	9.8	0.7	8.0	Years since the most recent regeneration period began	Remote sensing	$\bar{x} = 14.85$ y, $\sigma = 6.3$ y, max = 30 y, min = 3 y, $n = 180$
2	Precipitation	22.3	**13.9**	**15.9**	3.1	22.4	**10.6**	11.3	18.8	Mean annual precipitation (mm)	Precipitation WorldClim V1 Bioclim	$\bar{x} = 992$ mm y^{-1}, $\sigma = 191$ mm y^{-1}, max = 1308 mm y^{-1}, min = 582 mm y^{-1}, $n = 180$
3	Sampling cluster	17.4	10.1	13.7	5.1	**39.4**	8.6	**23.0**	**28.8**	Sampling cluster, representing location-specific factors and correlated with precipitation	Interviews and maps	N/A
4	Deforestation driver	12.9	2.9	0.6	6.9	9.5	6.4	−1.0	6.9	Index for the proximate deforestation driver (prior to the most recent regeneration period): 1 = cultivation, 2 = tree cutting (refugee camp, tobacco), 3 = charcoal, 4 = livestock, 5 = landslide or flooding	Interviews and observations	Cultivation = 154 (86%), tree-cutting = 13 (7%), charcoal = 10 (6%), livestock = 2 (1%), landslide/flooding = 1 (1%)
5	Vegetation	9.6	N/A			15.1	N/A			Vegetation class: Bushland (including thicket), Lowland Forest or Woodland	Classification based on species composition	N/A
6	Livestock[a]	7.0	−0.5	9.8	−5.2	18.0	4.7	6.0	8.1	A livestock-grazing intensity index: 4 = High. 12 months & >50 animals, 3 = Medium. Residual class between 2 & 4, 2 = Low. < 3 months & < 50 animals, 1 = No evidence of livestock-grazing	Interviews and observations	Total presence = 111 (62%) high = 59 (33%), medium = 47 (26%), low = 5 (3%), no livestock = 69 (38%)
7	Tree-cutting	6.8	5.0	−0.1	1.9	8.3	3.4	4.1	4.2	Presence/absence of tree-cutting, excluding tree-cutting specifically for charcoal production	Interviews and observations	37 (21%)

(Continued.)

Table 1. (Continued.)

Rank for influence on biomass	Variable	Mean accuracy decrease (%IncMSE): how much the RF model accuracy decreases, if we exclude the variable. Highest values per vegetation class are in bold — Above ground biomass: All	BA&BT	CL	MW	Species richness: All	BA&BT	CL	MW	Variable description	Data source	Number of plots in which the variable was present (% plots) or summary statistics (time, precipitation)
8	Cultivation	6.6	6.0	0.2	4.7	7.8	7.3	0.8	5.7	Presence/absence of cultivation at any point after 1987	Interviews and observations	155 (86%)
9	Fire	5.4	3.5	−2.1	2.2	6.7	−2.9	−2.5	4.6	Fire frequency in the plot, as an index: 4 = annually, 3 = regularly but not annually, 2 = occasionally/residual presence class, 1 = no evidence of fires	Interviews and observations	Total presence = 105 (58%) annually = 21 (12%), regularly = 41 (23%), occasionally = 43 (24%), no sign of fire = 75 (42%)
10	Conservation	2.8	0.0	1.3	1.0	9.0	0.0	6.7	11.0	Presence/absence of conservation designation. Includes village land forest reserves, wildlife management areas and government forest reserves	Interviews and observations	26 (14%)
11	Charcoal	−1.1	−2.5	1.4	2.8	7.8	4.3	1.9	0.9	Presence/absence of charcoal kilns or tree-cutting for charcoal production	Interviews and observations	34 (19%)

Vegetation classes BA: Bushland, BT: Thicket, CL: Lowland forest, MW: Miombo woodland.

[a] The influence on AGB of elephant and goat herbivory, recorded in 12 and 72 plots respectively, were tested but did not improve model accuracy.

The bold values indicates highest values per vegetation class.

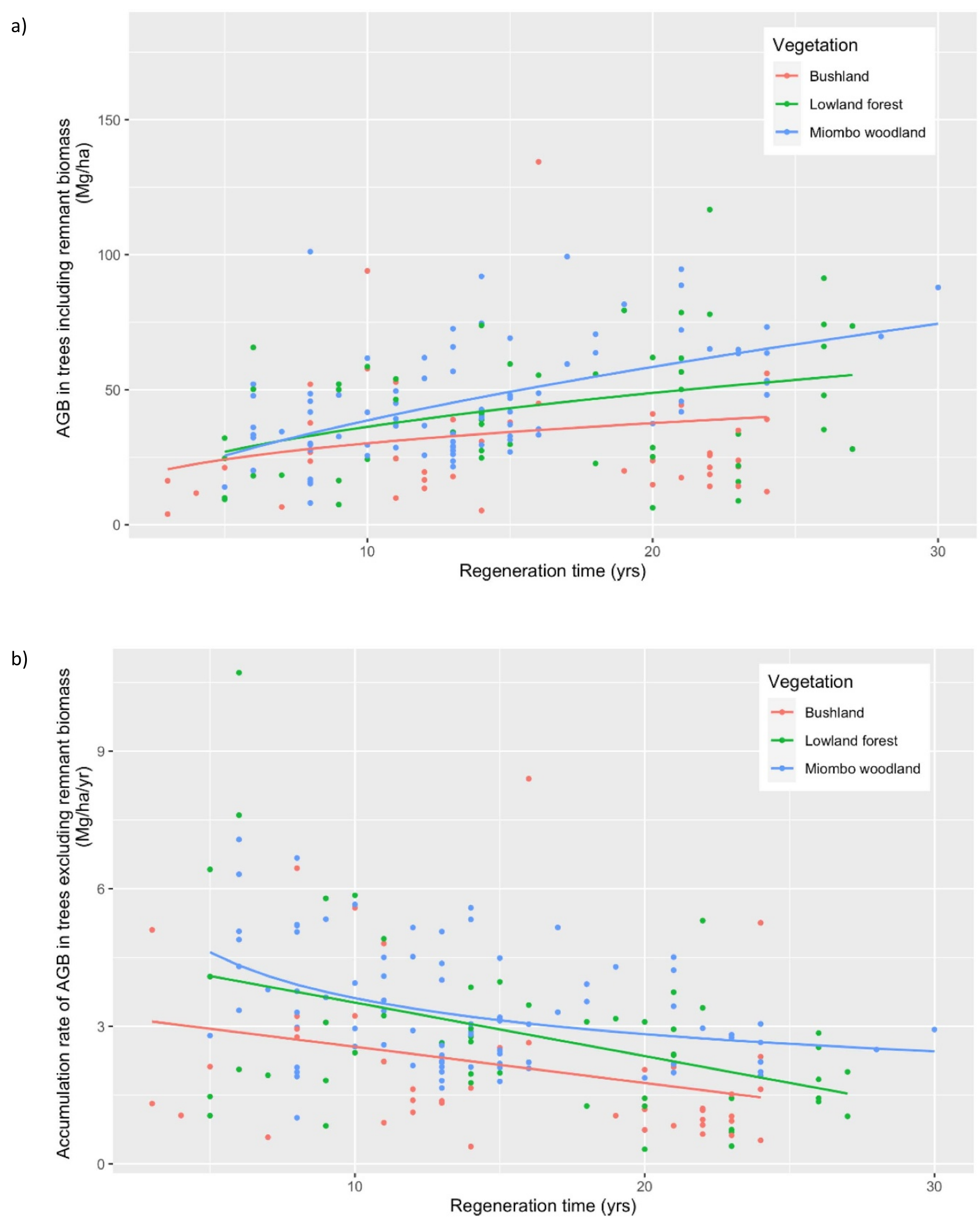

Figure 4. (a) Above ground biomass in trees (AGB), including remnant biomass, over time, showing nonlinear regression model trendlines (RMT) and (b) AGB accumulation rate, excluding remnant biomass, over time with linear RMT for bushland and lowland forest and non-linear RMT for miombo woodland. Model type (linear or non-linear) was selected based on the lowest Akaike Information Criterion for each vegetation type.

37 years for West African forest [18]. Stem stocking-density in the plots was high ($\bar{x} = 4594$ stems ha^{-1}, $\sigma = 7269$ stems ha^{-1}, range: 71–48 496 stems ha^{-1}) (table 2). 80% of stems were <10 cm dbh ($\bar{x} = 8.3$ cm dbh, median = 7.0 cm dbh, σ = 1.29 cm dbh, n = 14 310). Thus, although biomass increases rapidly, at 20 years only 20% of stems meet a 10 cm dbh minimum harvestable-stem criterion [58]. While the peak biomass accumulation rate supports a 10 year charcoal harvesting rotation, similar to other studies' recommendations of 8–15 years in MW [58] and 12–14 years in bushland [17], a 20 year rotation gives time for stems to reach 10 cm dbh.

3.4. Tree species richness

267 tree species were recorded in the 180 plots. Tree SR per FSSP ranged from 2 to 32 species/plot

Table 2. Summary values for above ground biomass (excluding remnant trees), species richness and stem density for all plots and disaggregated by vegetation type.

	Above ground biomass (Mg ha^{-1})				Species richness (number of species/plot)				Stem density (ha^{-1})			
Vegetation type	All	BA & BT	CL	MW	All	BA & BT	CL	MW	All	BA & BT	CL	MW
Min	3.9	3.9	5.3	8.0	2	2	2	4	71	198	71	722
Max	134.4	134.4	116.7	94.7	32	17	27	32	48 496	20 471	48 496	32 623
Mean	39.2	29.3	39.5	44.1	14	8	13	17	4594	2831	6396	4407
Standard deviation	22.8	26.5	22.7	19.2	7	4	7	7	7269	5101	9982	6021
Median	35.4	22.1	35.6	39.9	12	8	12	17	1514	806	1514	1691

($\bar{x} = 14$, $\sigma = 7.2$ species/plot) (table 2). The mean tree SR per FSSP for MW ($\bar{x} = 17$), lowland forest ($\bar{x} = 13$) and bushland ($\bar{x} = 8$) are all more than double the national inventory mean tree SR of 6, 6 and 3 per 15 m radius plots for the respective vegetation types [59]. The results contrast with other studies which have recorded no significant difference [55, 57] or slightly higher [46] SR in regenerating sites of >20 y or >30 y, compared with mature woodland, while younger regenerating areas had lower SR than mature woodland [60]. This may reflect the positive correlation between human activity and SR given the study's inherent bias in locating the FSSPs in post-cultivation areas [61].

Comparative studies of species composition in regenerating and mature African woodland indicate significant differences [16, 55, 57, 58, 60]. In contrast, the study found similarities between the common FSSP species and national forest inventory results whereby the five most common tree species in the FSSPs were *Julbernardia globiflora, Vachellia tortilis, Brachystegia spiciformis, Diplorhynchus condylocarpon* and *Uapaca kirkiana*, comprising 13.3%, 4.5%, 4.1%, 4.1% and 3.4% of all FSSP trees. All five species are in the top 16 most common trees in Tanzania, including three of the five most common species [11].

The RF regression across all plots showed that SR was influenced by location/district, precipitation, livestock-grazing, vegetation type and time, in order of importance (table 1, figure 5). For MW, conservation was influential. The RF models explained more of the variance in SR, than for AGB, with the highest proportion of variance explained by the RF model for SR for all vegetation types (64%). Least successful was the model for bushland AGB (22%). In general, the models performed poorly in the bushland class.

The mean species accumulation rate, calculated as SR over regeneration time, was 1.08 species y^{-1}, ($\sigma = 0.69$ species y^{-1}). It was higher in MW ($\bar{x} = 1.34$ species y^{-1}, $\sigma = 0.69$ species y^{-1}, $n = 86$) and lowland forest ($\bar{x} = 1.01$ species y^{-1}, $\sigma = 0.63$ species y^{-1}, $n = 51$) than in bushland ($\bar{x} = 0.63$ species y^{-1}, $\sigma = 0.5$ species y^{-1}, $n = 43$). The results are similar to rates recorded in Mozambique [60] and higher than in Zambia [16].

3.5. Carbon and climate implications

Regenerating forests on village land sequester 1.4 Mg C ha^{-1} y^{-1} (95% CI: 1.25–1.48 Mg C ha^{-1} y^{-1}) based on a mean AGB accumulation rate of 2.9 Mg ha^{-1} y^{-1} (95% CI: 2.66–3.15 Mg ha^{-1} y^{-1}) and 0.47 biomass-carbon conversion factor [46]. This is comparable to sequestration rates of 1.3 ± 0.3 Mg C ha^{-1} y^{-1} in the Brazilian eastern Amazon [48]. The 3.15 Mha of regenerating village land forests sequester approximately 4.3 Tg C y^{-1} (95% CI: 3.94–4.67 Tg C y^{-1}) equivalent to ∼36% of Tanzania's deforestation emissions (11.9 Tg C y^{-1} according to Tanzania's FREL) [15], a higher offset rate than the Brazilian Amazon [48, 62]. In terms of carbon storage, there were ∼58.14 Tg C (95% CI: 53.21–63.07 Tg C) (excluding remnant trees) in regenerating village land forests, in 2021.

3.6. Forest policy and management implications

Since agriculture is the main driver of both deforestation [63] and forest regeneration, more forestry-agriculture coordination is needed to optimise land allocation to meet both sectors' goals. The results show that long-fallows comprise a substantial spatial and temporal reservoir for carbon and biodiversity. While recognising their ephemerality, long forest-fallows, integral to shifting-cultivation, may offer win-wins for agriculture, climate and biodiversity relative to land solely under intensive agriculture. This requires policy support [64]. Forest conservation, both by communities and private landowners, is another policy-led regeneration driver, frequently detected by the study. The similarity in mean AGB between the studies' MW regeneration plots ($\bar{x} = 44.1$ Mg ha^{-1}) and national forest inventory results for open woodland ($\bar{x} = 42.5$ Mg ha^{-1}), indicates that naturally regenerating areas can attain comparable levels of AGB to surrounding vegetation within 5–10 years, often with negligible management. This gives empirical support to policy proposals to promote sustainable timber and charcoal harvesting in community-managed woodlands [65] and highlights natural regeneration's potential as a biodiversity-enhancing forest restoration tool [66, 67], with implications for the Bonn Challenge

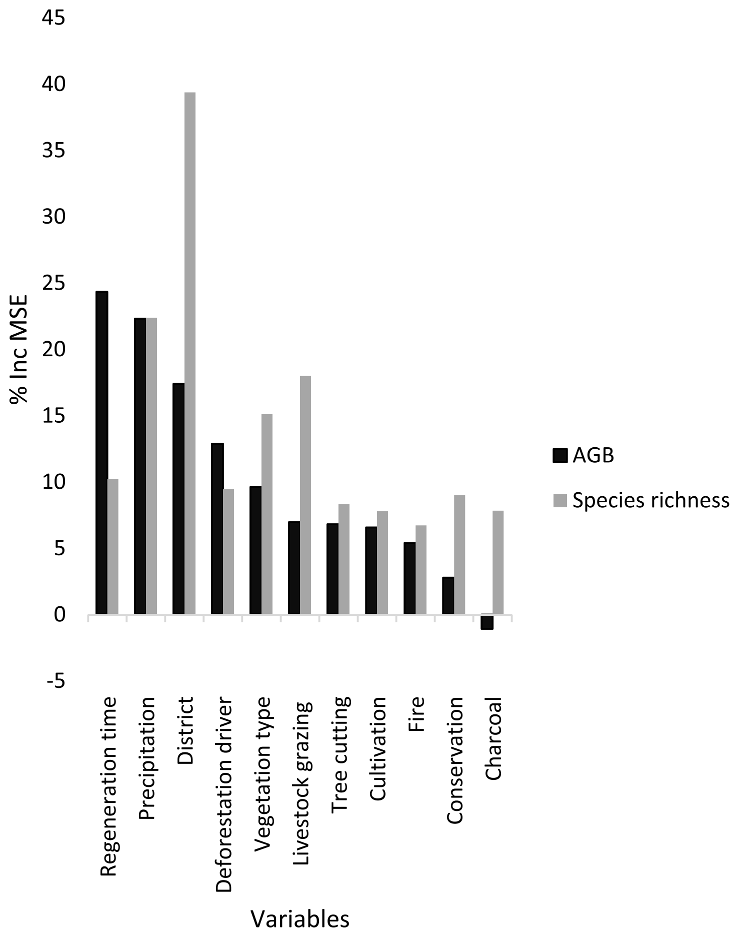

Figure 5. Influence of variables (% increase in the mean-squared error of the random forest regression model, if the variable is excluded) on above ground biomass (including stumps, excluding remnant trees) and species richness for all plots. See table 1 for a description of the variables.

and Tanzania's target to restore 5.2 million ha of forest by 2030 [68]. While it is necessary to exclude cultivation for natural regeneration to proceed, other activities including charcoal-production and livestock-grazing may be compatible in some habitats.

Tanzania has lost 32.46% of village land forests since 1987, a finding relevant to policies to reduce deforestation, including REDD+. In its Intended Nationally Determined Contribution, Tanzania committed to reduce greenhouse gas emissions by up to 8.35 Tg C y^{-1} [69]. The study indicates that village land natural regeneration is equivalent to 51.6% of this target.

4. Conclusions

Natural regeneration has the potential to contribute to global and national goals to restore forest cover, store carbon, conserve biodiversity and enhance livelihood resilience. However, in Tanzania, it is a rare land class with just 5.6% of village land under natural regeneration. In contrast, 22.2% of village land changed from forest to non-forest, predominantly to agriculture. Agriculture, primarily through fallows, is the main driver of natural regeneration. Biomass and species accumulation are most affected by time, precipitation and location. 10–20 year harvesting rotations for charcoal or other wood-based products would provide a balance between maximum biomass accumulation rates and minimum harvestable stem size. Despite their rarity regenerating forests accumulate over one third of Tanzania's annual carbon emissions from deforestation.

More research is needed on place-based factors affecting regeneration; bushland regeneration dynamics; and the potential for long-fallows to achieve positive agricultural, biodiversity and climate outcomes.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5518/1295. Results of the structured interviews are available upon reasonable request from the University of Leeds Restricted Access Repository (RADAR).

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Ethical approval

The research was reviewed and approved by the Research Ethics Committee of the University of Leeds. Reference: AREA 20-143.

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Chapter 5 The influence of energy policy on charcoal consumption in urban households in Tanzania

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The influence of energy policy on charcoal consumption in urban households in Tanzania

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ABSTRACT

The sustainability of energy use in the residential sector has relevance for global initiatives to achieve sustainable development and limit climate change. Using the city of Dar es Salaam, in Tanzania, as a case study, we look at how national energy policy has influenced household cooking energy use between 1990 and 2018, and how energy policy could achieve further progress to realise national and global priorities. The study involved questionnaire surveys of households, retailers, transporters and producers of charcoal; semi-structured interviews with government officials and non-charcoal fuel suppliers; price data collection; a comparative analysis of prices and taxes for different cooking fuels; and policy and document review. Trends in energy policy and demand for different fuels, are compared. We find that Tanzania's national energy policies have focused on achieving an energy transition from biomass to electricity and fossil fuels, with an increasing focus on supply-side issues. Fiscal policy tools have been used effectively to reduce demand for kerosene, while increasing demand for liquefied petroleum gas. However, this has not resulted in a transition away from biomass, with most households using multiple fuels (fuel stacking). Charcoal remains the cheapest (excluding firewood) and most widely used fuel, reflecting the strong influence of price in consumer fuel choices. Energy policy needs to acknowledge the continued dominance of charcoal in urban energy use. In the context of rapid urbanisation and increased energy demand, there is a need for sustainable urban energy planning across a range of fuel types including charcoal, in ways that balance economic, social and environmental outcomes. Greater inter-sectoral coordination is needed to improve the sustainability of urban residential energy supplies.

Introduction

Background to charcoal's place in urban energy supplies and energy policy

Reducing emissions of greenhouse gases, including from residential sources and land use change, whilst '*ensuring access to affordable, reliable, sustainable and modern energy for all (SDG 7)*' are global challenges codified in the Paris Agreement (UNFCCC, 2015) and the Sustainable Development Goals (SDGs), respectively. Achieving these global ambitions requires national policies to deliver relevant outcomes. In sub-Saharan Africa, the residential sector is the largest consumer of energy, primarily as biomass energy for cooking (Ouedraogo, 2017). Despite decades of national policies attempting to transition residential consumers away from biomass, it remains the main source of energy for 2.8 billion people globally (Bonjour et al., 2013), including 780 million in sub-Saharan Africa (IEA, 2018). While many models predict a decline in the relative importance of residential biomass consumption as a proportion of total energy consumption in sub-Saharan Africa, given urbanisation and increasing populations, there is little evidence that total demand will decline (Ouedraogo, 2017).

In most countries in sub-Saharan Africa, urbanisation has resulted in charcoal gaining in relative importance, while firewood declines (Girard, 2002). Charcoal is the main cooking fuel for most urban households across sub-Saharan African countries (Makonese, Ifegbesan, & Rampedi, 2018; van der Plas & Abdel-Hamid, 2005). Charcoal has been linked to a range of environmental and social problems (Sola et al., 2017) including climate change (Bailis, Drigo, Ghilardi, & Masera, 2015; Maes & Verbist, 2012), deforestation, forest degradation (Mwampamba, 2007; Zulu & Richardson, 2013), increased morbidity due to indoor and outdoor air pollution (Bruce, Perez-Padilla, & Albalak, 2000; Butt et al., 2016; Conibear, Butt, Knote, Arnold, & Spracklen, 2018; Roy, 2016) and political violence (Branch & Martiniello, 2018). Globally,

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woodfuels generate 1.9–2.3% of global greenhouse gas emissions (Bailis et al., 2015). To help address these issues, reducing charcoal consumption has been a policy goal in many African countries (Leach, 1992; Zulu, 2010). Policy tools that have been used to reduce consumption include criminalising charcoal production and/or trade (Zulu, 2010); subsidising alternative fuels (Hosier & Kipondya, 1993); and promoting fuel-efficient stoves (Maes & Verbist, 2012). In many countries, such policies have had limited success (Girard, 2002; Maes & Verbist, 2012). Charcoal bans have generally driven the trade further into informal ways of operating (Zulu, 2010). While the use of subsidies has been found to be more effective than bans, in influencing consumers, energy subsidies are often regressive and costly (Hosier & Kipondya, 1993; Maes & Verbist, 2012), replace one non-biomass fuel for another, such as liquefied petroleum gas (LPG) replacing kerosene (Leach, 1992), and/or result in a diversification of fuel types rather than a transition (Maes & Verbist, 2012). Even in countries, including Zimbabwe and South Africa, where subsidising electricity has contributed to its widespread uptake for domestic cooking, many households retain biomass fuels in their energy mix (Campbell, Vermeulen, Mangono, & Mabugu, 2003).

Charcoal's place in Tanzania's urban energy supply and energy policy

This study looks at the influence of energy policy on urban residential energy use in Tanzania. Residential energy consumption comprised 70% of total national energy consumption in 2017, a decline from 74% in 2002 (IEA 2005, 2019). The majority of the residential energy consumption (84% in 2002, 97% in 2017 (ibid.)) comes from biofuels and waste. In 2017, 90% of all households in Tanzania were using either charcoal (21%) or firewood (69%) as their main source of energy for cooking (URT, 2019). The primacy of biomass energy has changed little since 1989 when 92% of final energy consumption came from firewood, charcoal and agricultural residues, of which 80% was used in the residential sector (URT, 1992). Given urban households' preference for charcoal over firewood, urbanisation drives a shift from firewood to charcoal. Tanzania is the fifth largest producer of charcoal in Africa and the charcoal trade in Tanzania is one of the most frequently studied charcoal trades in Africa (FAO, 2016; Sola et al., 2017).

Policy-makers in Tanzania have sought to reduce urban households' dependence on charcoal as a way of reducing deforestation (Doggart & Meshack, 2017) and air pollution, and pursuing a broader modernisation agenda. The first national energy policy was adopted in 1992, with revised policies being adopted in 2003 and 2015. All three policies have included objectives seeking to transition away from biomass energy and into electricity and fossil fuels (URT, 1992, 2003; URT, 2015). They differ in the declining emphasis placed on improving the sustainability of biomass energy production. For example, the 1992 policy includes two objectives aiming to improve biomass energy production and efficiency for residential use, whereas the 2015 policy only considers biomass in the context of electricity generation. The 2015 policy notes that despite the promotion of modern energy supplies in previous policies, they remain expensive and inaccessible to most Tanzanians. Based on these challenges, the policy prioritises improving the business environment and increasing access to modern energy supplies. However, despite three decades of aspiring to an energy transition, charcoal remains persistently popular in Tanzania's cities, a policy tension highlighted in several previous studies (CHAPOSA, 2002; Peter & Sander, 2009; CamCo, 2014) and mirroring tensions experienced in many other tropical countries (Leach, 1992).

Tanzania's policy has its theoretical roots in the 'energy transition model' (Leach, 1992). Energy policies seeking to transition households from biomass energy to fossil fuels and electricity assume that consumers perceive biomass energy, including both charcoal and firewood, to be inferior goods. Thus, with increased incomes, it is assumed that households will climb the 'energy ladder' from biomass energy, through kerosene, LPG and on to natural gas and electricity, the so-called 'modern' fuels. This pathway is known as the 'energy transition' and has been considered as, '*a basic feature of economic growth*' (ibid). Fuel availability and the price of the fuel and cooking appliances are considered to be the key obstacles to households climbing the energy ladder. While some countries have followed this transition, other countries have followed a different trajectory, in which, as households grow wealthier, they use multiple fuels in increasingly complex ways, a behaviour known as 'fuel stacking' (Hiemstra-van der Horst & Hovorka, 2008; Choumert, Combes Motel, & Le Roux, 2017; Maes & Verbist, 2012; Masera, Saatkamp, & Kammen, 2000). Instead of substituting fuels, as the energy transition predicts, households diversify fuel use. In Tanzania, there is clear evidence of households moving away from firewood with urbanisation and increasing incomes (D'Agostino, Urpelainen, & Xu, 2015), thus following the energy transition model. However, instead of transitioning to 'modern' fuels, firewood is substituted by charcoal in combination with one or more additional fuel types in a fuel-stacking pattern. The market treats charcoal as a normal good with demand positively correlated with household income (d'Agostino et al., 2015). Multiple reasons can account for this, including charcoal's relative price and availability, cultural preferences and the advantages of fuel-stacking over transitioning in terms of household energy efficiency and security (Makonese et al., 2018; Ruiz-Mercado & Masera, 2015).

Focal questions for the study

In this study, we consider four questions:

1. Is there evidence of an energy transition from biomass energy to 'modern' fuels between 1990 and 2018 in Dar es Salaam?
2. Have the policy tools that have been used to influence the urban residential energy sector, achieved the expected policy outcomes, and at what cost?
3. What are the implications for national energy policy of households diversifying rather than transitioning their cooking energy supplies?
4. How can national energy policies be more effective in achieving outcomes compatible with both national priorities and with global goals around climate change and sustainable energy supplies?

The study adds new empirical evidence of fuel-use behaviour providing additional insights into the tensions between energy policy and household practices; and proposes a re-orientation in energy policy to place more emphasis on matching demand and supply, inter-sectoral coordination and global sustainability goals. The paper is organized as follows: section 2 describes the study location and methods; section 3 presents the main results of the study; section 4 includes a discussion of how the study's results address the four questions listed above; section 5 presents recommendations for further research; and section 6 summarises key conclusions of the study.

Study location and methods

Study location

Dar es Salaam - the commercial capital and largest urban area in Tanzania with 4.3 million people, comprising 37.4% of the total national urban population at the time of the last census in 2012 - was selected as the focus for this case study. The intercensal growth rate between 2002 and 2012 was 5.6% per annum and the projected population for the study period, in 2018, was 5.96 million (NBS, 2013, 2016). Tanzania is becoming increasingly urbanised with the proportion of the population living in urban areas increasing from 19% in 1990 to 34% in 2017 (UNDESA-PD, 2018). The average household size in Tanzania is 4.6 people, with urban households being smaller, on average, (4.2) compared with rural households (4.9) (NBS, 2019).

Dar es Salaam is a coastal city, important for trade and manufacturing and was the capital of Tanzania until 1974. We selected Dar es Salaam firstly because it has the largest charcoal market in Tanzania being home to approximately 30.3% of Tanzania's urban population, by 2015 (Worrall et al., 2017) and secondly due to the availability of historical studies (Hosier, 1993; CHAPOSA, 2002). The city is divided into 5 municipalities: Ilala, Kigamboni, Kinondoni, Temeke and Ubungo. Municipal councils are responsible for promoting social and economic development, and maintaining peace and order. A City Council, headed by the City Mayor, promotes coordination between the municipal councils and is responsible for inter-municipal issues, including transportation. A Regional Administration headed by the Regional Commissioner, provides an additional layer of government between local and central government.

The study focused on Dar es Salaam but has relevance to other urban areas in Tanzania and sub-Saharan Africa. Studies of other urban areas in Tanzania show comparable patterns of household fuel use (Hosier & Kipondya, 1993; Mwampamba, 2007). For example, the 2017/18 household budget survey found that 60.5% of all urban households use charcoal as their main cooking fuel, compared with 58.9% in Dar es Salaam (NBS, 2019). Similarly, there are many commonalities between cooking fuel use patterns, trends and policies in Tanzania, with other countries in sub-Saharan Africa (Makonese et al., 2018).

Overview and timing of data collection

The study involved interviewer-administered questionnaires with households, retailers, wholesalers, transporters and producers of charcoal; key informant semi-structured interviews with government officials and non-charcoal fuel suppliers; price data collection; and policy and document review. The data collection was carried out between October and November 2018 in Dar es Salaam Region, and, in the case of charcoal producers and transporters, in the adjacent regions of Morogoro (Mvomero and Morogoro Districts) and Coast (Kisarawe and Kibaha Districts), as well-documented sources of charcoal for Dar es Salaam (Malimbwi & Zahabu, 2008).

Household questionnaire surveys

Questionnaire interviews on domestic energy use were carried out in 100 households across the city's five municipalities. The sample size was calculated to give a margin of error ≤ 10% at a 95% confidence level).

Population and sampling

A stratified random sampling approach was used to select the households where the stratification was based on urban wards across Dar es Salaam Region. Household sampling used the 2012 census ward shapefile provided by the National Bureau of Statistics. Sampling intensity in each ward was based on the ward's relative contribution to Dar es Salaam's population. An urban ward was defined as a ward with a population density of 2000 people per sq. km. Only urban wards were included. Initial sampling locations were generated at random within the urban wards, using the random points tool in QGIS. The wards in southern Kigamboni were excluded from consideration because they did not meet the definition of urban. Twelve other wards did not receive sample points because their relative contribution to population was too low. Overall, there were no sample points in wards that cumulatively held 4.5% of the total population of Dar es Salaam Region. Table 1 compares the sampling intensity with the population of the five municipalities.

The sample points were overlaid on Google Earth high resolution imagery. The residential building closest to the sample point was selected as the sample household. Two reserve points per sample point were selected at the next two nearest residential buildings. In the event that the survey could not proceed at the original sample household, one of the reserve points was used. Finally, sample households were loaded into google maps to make it easy for interviewers to navigate to the households.

Table 1
Population distribution and sample intensity across the five municipalities of Dar es Salaam.

Municipality	Population (NBS, 2017)	% of the Dar population	Total sample points
Kinondoni	1,231,516	21%	23
Ilala	1,616,901	28%	28
Temeke	1,597,479	28%	26
Ubungo	1,119,830	19%	19
Kigamboni	215,830	4%	4
Total	5,781,556	100%	100

Data collection

A conditional branching questionnaire was developed, using the online KoBo Toolbox survey tool. The questionnaire was pre-tested with 4 households. The results from the pre-testing were included in the final survey. The survey tool included questions about: the current mix of cooking fuels used by the household; the amount of each fuel purchased, fuel prices and expenditure; reasons for using each fuel type; reasons for not using Liquefied Petroleum Gas (LPG), electricity and/or charcoal (where relevant); types of food cooked with each fuel; and energy saving techniques applied by the household. Cooking fuels that were considered in the survey included: briquettes, charcoal, electricity, ethanol gel, firewood, kerosene, LPG and an 'other' category to cover energy sources such as biogas, solar and natural gas.

Data analysis

We prepared descriptive statistics from the results of the household questionnaires to provide an overview of fuel use in 2018 and compared these with results of previous surveys including three Household Budget Surveys in 2000/1, 2007 and 2011/12, the 1990 Tanzania Urban Household Survey as reported in Hosier and Kipondya (1993) and the 2016 Energy Access Situation Report (NBS, 2017). These five earlier surveys are comparable with the current study in using household questionnaires and in using the regional boundary for Dar es Salaam as one of their sample units. All five surveys produced data on average household fuel use, albeit based on different sample sizes and sample selection methods. These five surveys provide the best available datasets from which to detect trends, relevant to the study.

The temporal gap between the historical data points ranges from 5 to 10 years. Whilst this creates a potential limitation by missing fluctuations occurring in the intervening periods, we recommend ways to improve monitoring of energy use patterns, in future.

Questionnaires with actors along the charcoal value chain

Population and sampling

The charcoal value chain involves four key steps: production, transportation, retail/wholesale and consumption (Sander, Gros, & Peter, 2013). To reflect this, the study included questionnaire interviews with actors along the value chain including producers, transporters, retailers and wholesalers.

Producers: 35 Producers were selected opportunistically from eight charcoal-producing villages in three districts (Kibaha, Kisarawe and Mvomero) within 180 km of the centre of Dar es Salaam (Table 2). We estimated that there are approximately 62,500 producers supplying charcoal to Dar es Salaam based on an annual production rate of 8 t/producer (van Beukering, 2007) and 500,000 t of charcoal consumed in Dar es Salaam annually (Peter & Sander, 2009).

Transporters: 35 transporters were included in the survey among those working within 180 km of Dar es Salaam. This included transporters in: Kibaha (19), Kinondoni and Ubungo Municipalities (14), Kisarawe (2) and Morogoro (1). Transporters were selected opportunistically from those waiting to pass through government check points on the main east-west highway coming into the city. Van Beukering (2007)

Table 2
Number of charcoal producers interviewed per village.

District	Village	Number of producers interviewed
Mvomero	Doma	4
	Mkata	4
	Mangae	4
Kibaha	Kwala	3
	Dutumi	7
Kisarawe	Panga la Mwingereza	5
	Mafumbi	5
	Kirui Chole	3
Total		35

estimated that 0.9 million person years were utilised in transporting charcoal to Dar es Salaam annually.

Retailers and wholesalers: the study was designed to include 20 retailers and 20 wholesalers. Retailers sell charcoal directly to consumers, usually from small shops close to residential areas. Shops are usually open-fronted and the charcoal is sold in small bags, tins or buckets. We estimate that there are >12,000 retailers in Dar es Salaam although precise data on the number of retailers is not available. Our estimate is based on retailers selling an average of 39 t of charcoal per year and a total trade volume of at least 500,000 t per year (Peter & Sander, 2009). Over the course of the study this was increased to 24 retailers. Wholesalers sell charcoal to retailers, usually by the sack. Over the course of the study, sampling was revised to 7 wholesalers. Reasons for the reduced sample of wholesalers are outlined in Section 3.5. The survey tools for the producers, transporters and retailers/wholesalers included questions on pricing, type and source of charcoal traded, volume and costs of trade, regulatory compliance, and trend perceptions. The margin of error (95% confidence level) for the tax compliance rates for producers, transporters and retailers were calculated based on a binomial distribution using the sample size and assumed population size.

All questionnaire data were recorded using the Open Data Kit application https://opendatakit.org and exported to Excel for analysis.

Key informant interviews with government officials and non-charcoal fuel suppliers

Semi-structured key informant interviews (KIIs) were conducted with ten Local Government Authority (LGA) staff, six Central Government staff from the Tanzania Forest Services Agency (3), the Forestry and Beekeeping Division, the Tanzania Revenue Authority and Ministry of Energy, two LPG distributors and one briquette manufacturer. Interviews with the government staff included questions on the role of the respondents' government office in planning and regulating domestic cooking fuel value chains and on the collection of taxes, royalties, fees and other government revenues from household cooking fuels. Interviews with private sector suppliers of biomass briquettes and LPG covered product pricing, the regulatory and fiscal environment and plans for the future. The interviews were designed to provide qualitative depth to the study, exploring particular issues relevant to stakeholders' role in relation to household energy supply chains.

Energy price survey

Sampling and data collection

Charcoal - Charcoal prices were collected through the retailer questionnaires described above. Weights of charcoal sold in small bags, tins, buckets and sacks were measured with spring balances to give an accurate price per kilogram.

Electricity and kerosene - Prices for electricity and kerosene are set periodically by the Government. Prices for these energy types were determined with reference to relevant government documents. Official prices were compared with prices at selling points to confirm that the official prices are those applied.

Ethanol and briquettes - Prices for briquettes were collected through the KIIs while prices for both briquettes and ethanol were surveyed by visiting two known retailers for one or other of the fuels and three other shops, in Kinondoni Municipality. As neither of the two products is widely used, the prices from these outlets were considered sufficient for the comparative price analysis.

Data analysis

On the assumption that price is a key determinant of consumers' fuel choices, we explored price differences between fuels and the contribution of indirect taxes and forest product royalties on fuel prices. As a first step in the analysis, we converted each of the prices into a price per unit of energy measured in Tanzanian shillings per megajoule (TZS/MJ) using standard conversion factors (CamCo, 2014). As a further step, considering that different fuel types convert into usable energy with different efficiencies, we then calculated the price per unit of useful energy, using values from CamCo, 2014. We repeated this for the taxes. Useful energy is defined as energy delivered to the pot, considering differences in the efficiency with which the energy contained in different fuels is transferred to the end use, in this case cooking (Bhattacharya & Abdul Salam, 2002). Firewood was not included in the comparison as the majority of firewood-using households collected firewood themselves, with no financial cost or tax.

Policy review

Policy documents were reviewed including policies, master plans, regulations and plans in the energy and forestry sectors, annual budget speeches from the Ministry of Finance and annual reports by the Energy and Water Utilities Regulatory Authority (EWURA). Data on domestic fuel use from the national budget survey and the national energy access situation reports were reviewed for comparisons (see Supplementary Materials for a list of the documents reviewed).

In our review of fiscal policies, we have only considered indirect taxes such as Value Added Tax (VAT), and royalties. Suppliers of LPG, briquettes, electricity and ethanol are also liable to pay a range of payroll taxes, as well as corporate income tax.

We prepared a timeline of key policy documents and decisions using the document review and KIIs, and compared these with the trends in household fuel use, in order to detect whether the desired policy outcomes were reflected in trends in household behaviour.

We compared policy objectives with consumer priorities to detect similarities and differences.

Definitions

We define charcoal as the '*solid residue derived from carbonization distillation, pyrolysis and torrefaction of fuelwood*,' (FAO, 2004).

We use the term 'modern fuels' to include LPG, natural gas, kerosene and electricity. This definition is adopted from Tanzania's National Energy Policy. We explore the issues around excluding biomass energy from the concept of energy modernity, in the discussion section.

Results

Household cooking fuel use status in 2018

The results of the household survey show that charcoal was the most popular household cooking fuel in Dar es Salaam in 2018, both as the main fuel (56% of households) and as part of a broader fuel mix (88% of households) (Fig. 1). LPG is the second most popular fuel, both as the main fuel (32%) and as part of the cooking fuel mix (58%). While kerosene is frequently used by households as part of the fuel mix (28%), only 3% of households use it as their main fuel. Similarly,

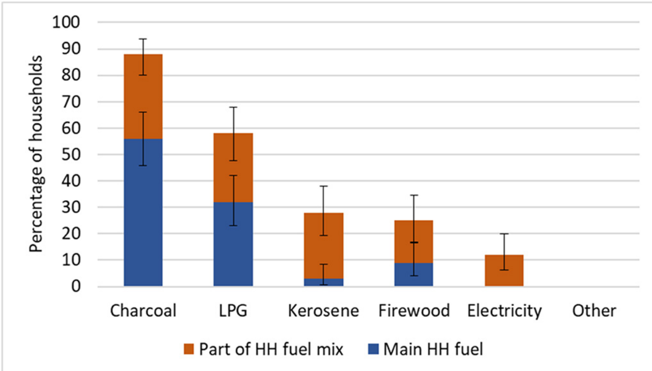


Fig. 1. Cooking-fuel types used by households in Dar es Salaam. Households list their main fuel, and other fuels as part of a fuel mix, if multiple fuels were used. Values are based on household surveys conducted in 2018. Note that there was no limit to the number of fuels that households could include when listing their fuel mix, while only one fuel could be described as the main fuel. Confidence intervals are shown calculated in r using the binom. test tool.

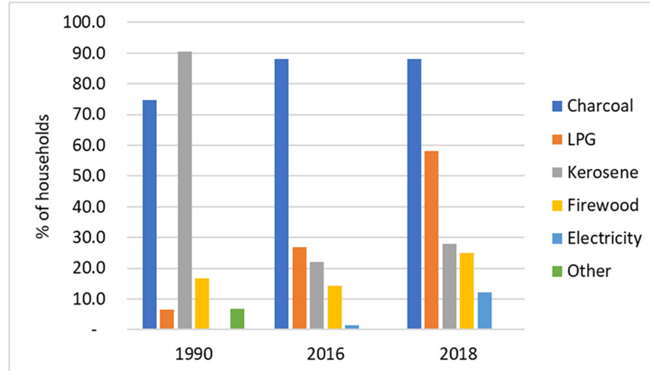


Fig. 3. Changes in the percentage of households using five cooking-fuels in Dar es Salaam between 1990 and 2018. Data sources: 1990: Hosier & Kipondya, 1993; 2016: National Bureau of Statistics Energy Access Situation Report (NBS, 2017); 2018 current survey.

firewood is only used by 9% of households as their main fuel and by 25% of households as part of the fuel mix. No household uses electricity as their main fuel and only 12% use electricity as part of the cooking energy mix.

Household cooking fuel use trends between 1990 and 2018

Fig. 2 compares results from our 2018 household surveys with Tanzania's household budget surveys that recorded the main household cooking fuel in Dar es Salaam in 2001, 2007 and 2012. Between 2001 and 2018, there has been a strong decline in kerosene use as the main fuel from 42% in 2001 to 3% in 2018. Between 2001 and 2007, charcoal replaced kerosene as the main household fuel. Between 2012 and 2018, increasing use of LPG as the main household fuel matches a decline in kerosene and charcoal as the main fuel.

Fig. 3 contrasts the results of our household survey with the 1990 Tanzania Urban Household Energy Survey (Hosier & Kipondya, 1993) and the Energy Access Situation Report 2016 (NBS, 2017). These surveys recorded all fuels used by households, in contrast to the household budget survey (Fig. 2) that only recorded the main household cooking fuel. Fig. 3 shows that charcoal has remained an important part of the fuel mix, with 75% of households using charcoal in 1990 increasing to 88% in 2018. Kerosene use has fallen dramatically, from 90% of households in 1990 to 28% in 2018. LPG was very rarely used in 1990, but increased to nearly 30% of households in 2016 and 58% in 2018. The rapid increase in LPG use between 2016 and 2018, matches national LPG imports which increased by 70% from 71,311 Metric Tonnes (MT) in 2015/16 to 120,961 MT in 2017/18 (EWURA, 2016, 2018a).

Fourteen different fuel combinations were recorded by our 2018 survey with a charcoal/LPG mix as the most frequently used combination (Fig. 4). Only 20% of households use only one fuel (i.e. 13% charcoal only, 5% LPG only and 2% firewood only), with 52% of households using two fuels, while 25% use three fuels, and 3% use four fuels. On average, households use 2.1 different fuels for cooking.

Reasons for household fuel preferences

Fig. 5 presents the reasons that households select different fuels for cooking. While having a fuel that can quickly be turned on and off was the reason cited most frequently for fuels being included in the fuel mix (Fig. 5a), affordability was the most frequent response for the selection of households' main fuel (Fig. 5b). Other reasons included a preference for LPG during the rainy season when charcoal was more expensive and it is difficult to cook outside; and having back-up fuels when the main fuel ran out within the household.

Respondents in the household surveys also stated their reasons for not using particular fuels. For both LPG and electricity, >90% of

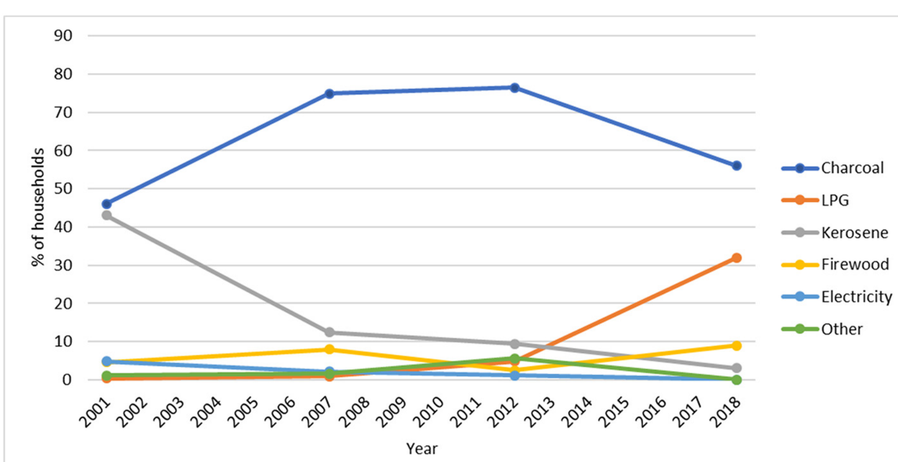


Fig. 2. Trends in the main household cooking fuel in Dar es Salaam between 2001 and 2018. The chart uses data for Dar es Salaam from Household Budget Surveys in 2000/1, 2007 and 2011/12 combined with the results of our survey in 2018.

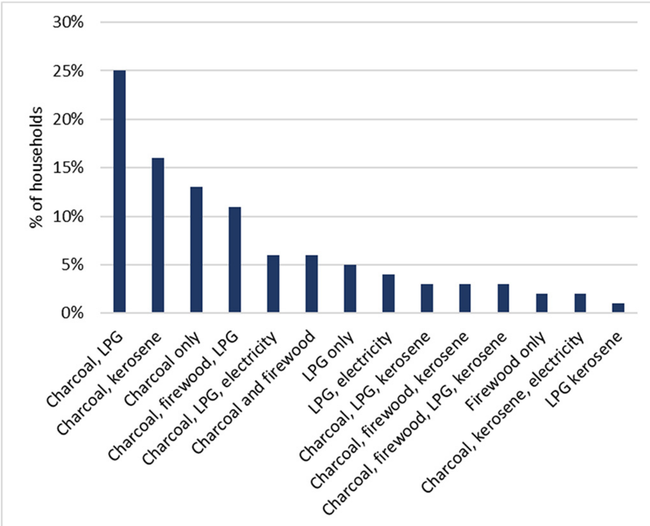


Fig. 4. Cooking fuel combinations used by households in Dar es Salaam in 2018.

households who did not use the fuel stated that the fuel was too expensive, while, in the case of kerosene, 59% of respondents who did not use kerosene, complained that it was messy, smoky or spoiled the taste of the food.

Cultural preferences can affect cooking fuel choices (Ruiz-Mercado & Masera, 2015). In order to understand the degree to which choice is influenced by cultural preferences, we asked about fuel preferences in preparing different foods. In the two-fuel LPG/charcoal households, we found that the majority (92%) of households will only prepare beans, using a charcoal stove. Meat and rice were also more likely to be cooked using charcoal, while breakfast porridge and leafy greens were more likely to be cooked using LPG. For other foods, no clear pattern emerges, and even within households the two fuels may be interchanged for preparing different food types.

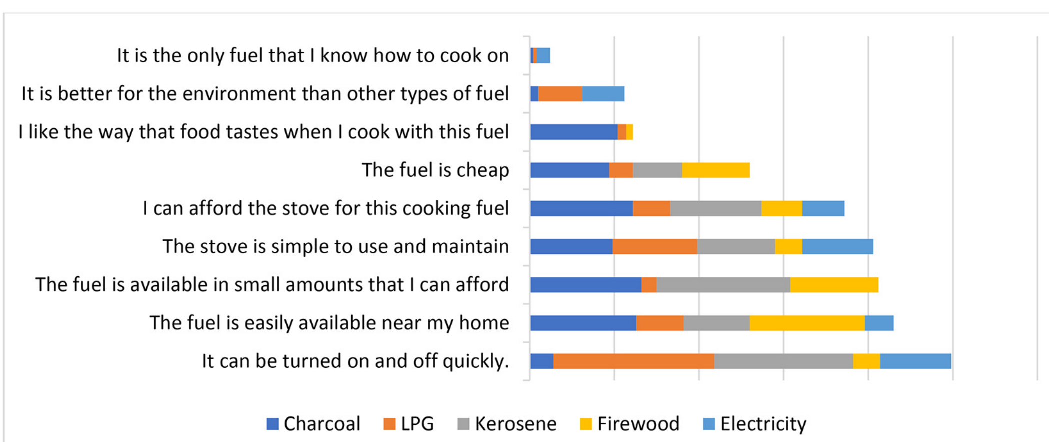
In terms of fuel-efficiency measures practiced by households, 34% of households stated that they regularly soak beans prior to cooking and 10% of households sometimes use a pressure cooker. Other fuel-efficiency strategies that were mentioned by households include cooking in bulk (11%) and stopping the charcoal or firewood from burning when cooking is finished, for later re-use (16%).

Fuel prices and taxes

The household surveys highlight the importance of affordability in fuel choice-making. The results of the price survey data allow us to explore whether consumers' perceptions of affordability match with the relative price per unit of energy, of the different fuels.

The comparative price analysis indicates that the two most popular fuels, charcoal and LPG (Fig. 1), are the cheapest per unit of energy, while the least popular fuels, ethanol and briquettes, are the most expensive (Fig. 6).

a)



b)

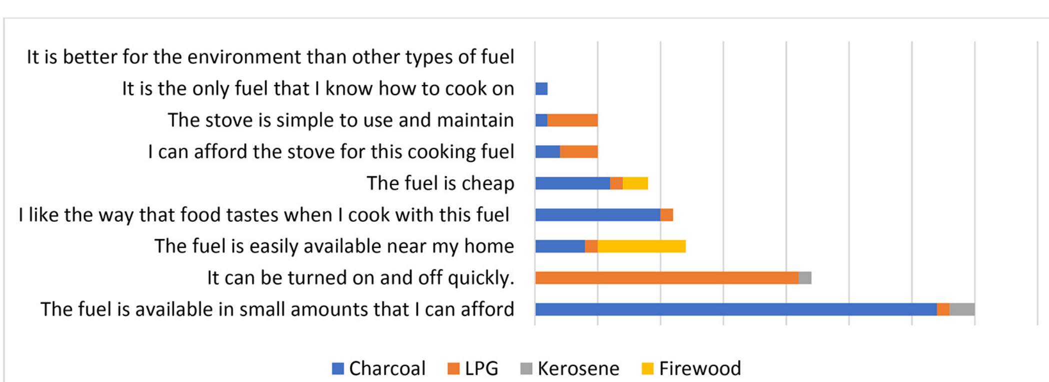


Fig. 5. Reasons for household fuel selection. a) Reasons mentioned by households for selecting fuels for use either individually or in combination with other fuels. Multiple responses were allowed. b) Households' most important reason for selecting their main fuel type. This was a follow up question to the question on main fuel type. Only one response was allowed.

From a policy perspective, Fig. 6 and Table 3 demonstrate how fiscal policies have affected the relative prices of the different fuels. The highest tax rates per unit of useful energy are for ethanol (TZS 60/MJ) and kerosene (TZS 42/MJ), while the rate for LPG is the lowest. The tax exemption for LPG has made it cheaper than electricity and kerosene. If the TZS 26/MJ in taxes on electricity were removed, it would be cheaper at TZS 116/MJ, than LPG which costs TZS 126/MJ. Similarly, in the case of kerosene, removing the TZS 42/MJ in duties and levies would make it cheaper at TZS 112/MJ, than LPG. In the case of briquettes and ethanol, both products would remain more expensive than LPG and electricity, even if they were exempted from all taxes. Charcoal, electricity and briquettes have comparable rates at between TZS 25.5–30/MJ (Table 3). However, it is charcoal's low pre-tax price that has made it the most affordable of the six fuels. If we take away the TZS 30/MJ of royalties in the charcoal price, we are left with a price of TZS 59/MJ equivalent to less than half of the LPG zero-tax price of TZS 126/MJ. This suggests that it would require a tax rate on charcoal of >100% to reach a comparable price with LPG.

While the average price of charcoal is lower than that of other sources of energy (Fig. 6), the price is highly variable. Table 4 shows that the prices of charcoal recorded during the survey ranged from 385 to 1430 TZS/kg fuel (mean ± standard deviation = TZS 776 ± 243). In general, it is cheaper to buy charcoal by large sack than by small plastic bag or by bucket (Table 4). The weight of charcoal in differently sized selling units was found to be highly variable. For example, the weight of charcoal sold in a 10-l bucket could vary from 2.8 kg to 4.2 kg. This is caused by differences in charcoal density and by the way that the charcoal is placed into the container. By using units of volume e.g. tins or buckets, as the units of sale, the price per unit of energy is highly variable given that the energy generated by charcoal will depend more on its weight than the volume of the container in which it is packaged. Charcoal's high price variability therefore suggests that, while consumers are correct in selecting charcoal for its overall affordability, it can be more expensive than LPG and electricity per unit of energy. For example, consumers who purchase a 1 kg plastic bag of charcoal for TZS 1429 will pay TZS 164/MJ of useful energy, making it more expensive per MJ, than electricity, LPG or kerosene.

Stakeholder perspectives

Local and central government

In terms of the mandate of different parts of government, for overseeing household energy supplies in Dar es Salaam, local government representatives responded that issues of urban energy supply were outside of their mandate. The Ministry of Energy respondent stated that their role is to increase supplies of modern energy for urban households pointing to the Power (electricity) Sector Master Plan (URT-MEM, 2016a), the Natural Gas Utilisation Master Plan (URT-MEM, 2016b), and the promotion of LPG. Both local government and the Ministry of Energy respondents indicated that woodfuel supplies were within the mandate of the Ministry of Natural Resources and Tourism (MNRT). Within MNRT, representatives from the Forestry and Beekeeping Division and the Tanzania Forest Services Agency described their role with regard to charcoal as including policy development, management of the charcoal trade and revenue collection. In response to questions around the regulatory challenges associated with the informal nature of the charcoal trade, TFS rejected the characterisation of the trade as being ‘informal’. Instead, they described revenue collection challenges including traders avoiding checkpoints and weak coordination between different stakeholders involved in the charcoal trade. In contrast, the Tanzania Revenue Authority (TRA) explained that VAT is not collected on charcoal because it is considered to be part of the ‘informal sector’ business category and because annual returns of charcoal traders do not meet the income threshold required for businesses to register for VAT. TRA added that discussions are ongoing around collection of VAT on charcoal.

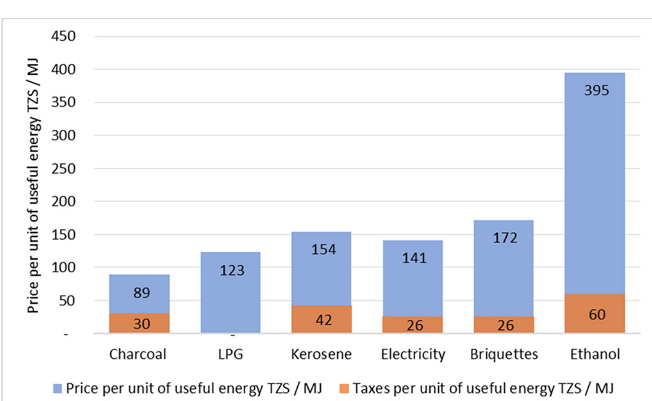


Fig. 6. Fuel price comparisons per unit of useful energy (Tanzanian Shilling (TZS)/MJ). The exchange rate at the time of the study was 1 US$ = 2284 TZS. The fraction of total fuel price that is comprised of indirect taxes is indicated.

Private sector

LPG suppliers stated that they anticipate, and are ready for, increasing demand for LPG. Investing in infrastructure and making LPG available in a broader size-range of tanks and cylinders are some of the strategies already being implemented. For example, LPG can now be bought in 3 kg cylinders making it more affordable for poorer households. Key concerns for the LPG suppliers were harmonisation of taxes and regulations; and LPG-related disaster preparedness and mitigation, including quality control for gas stoves.

Fig. 7 presents the study results on the kinds of taxes and fees that charcoal retailers, transporters and producers pay. The most frequently cited fees and tax were the TFS royalties, the wholesaler and trader licence fees also payable to TFS and the district agricultural tax payable in the district where charcoal is produced, known as ‘cess’. VAT was not mentioned by any of the respondents. During the field survey, few wholesalers were identified while in some cases retailers were selling both by the sack and in smaller amounts. In the latter case, they were included in the retailer category while overall the wholesaler sample size was reduced from 35 to 7, of whom 5 paid TFS registration fees and 2 paid municipal business licence fees.

National energy policy trends between 1990 and 2018

Fig. 8 presents a timeline of key energy policies in Tanzania. Tanzania's national energy policies have consistently sought to transition the residential sector away from firewood and charcoal. *Arresting woodfuel depletion* (URT, 1992), *reversal of deforestation* (URT, 2003 and *reducing deforestation* (URT, 2015a) are cited as energy sector issues that the three policies have sought to address through this transition. While the 1992 National Energy Policy focused on transitioning to electricity, coal and biogas, the 2003 policy emphasised efficiency gains while still promoting coal as an alternative for household cooking. In 2006, LPG was exempted from the fuel levy and from VAT on gas cylinders in order to persuade urban households to transition from charcoal to LPG. The emphasis on transitioning households to LPG was then embedded in the 2015 National Energy Policy stating, ‘*the Government has been promoting substitution of charcoal and firewood by providing tax relief to stimulate the use of LPG in the country*,’ (URT, 2015a). In 2016, master plans were published for the electricity and natural gas subsectors including long term aspirations for both energy sources to play a greater role in meeting residential sector demand, including as cooking fuels to substitute biomass energy. For example, the natural gas utilisation master plan includes the objective, ‘*To promote the use of natural gas as an alternative fuel to charcoal and wood for domestic use*’ (URT-MEM, 2016a) while the electricity master plan states ‘*In the*

Table 3
Price per unit of energy of different cooking fuels used by households in Dar es Salaam in October 2018.

Fuel Type	Price	Taxes, royalties duties and levies	Conversion factor to MJ	Price per unit of energy	End use cooking efficiency	Price per unit of useful energy	Tax per unit of useful energy
	TZS per unit	TZS per unit		TZS per MJ		TZS per MJ (US$/MJ)	TZS per MJ
Charcoal	776/kg	262.5/kg	29 MJ/kg	26.76	0.3	**89.20** (0.039)	30
Charcoal price: TZS 776/kg is the average price across the different units of sale (see Table 4).							
Charcoal royalties and levies: TZS 262.5/kg is based on a royalty of TZS 250/kg (95% to the Tanzania Forest Services Agency and 5% to Local Government Authorities (LGA)) plus TZS 12.5/kg for the LGA tree-planting levy. Although charcoal is not exempted from VAT, the Tanzania Revenue Authority (TRA) confirmed that they do not collect VAT from charcoal as TRA class charcoal as an informal industry.							
LPG	3333/kg	0/kg	45 MJ/kg	74.07	0.6	**123.44** (0.054)	0
LPG price: TZS 3333/kg is the most representative price for household LPG use. The standard retail price of LPG varied from TZS 2750/kg for a 38 kg cylinder to TZS 3333/kg for the 3 kg, 6 kg and 15 kg cylinders from Oryx, in Dar es Salaam. Oryx were the largest supplier of petroleum products in 2017/18 (EWURA, 2018a). During the KII, the Oryx representative stated that the 6 kg and 15 kg cylinders were the most popular.							
LPG tax: As LPG is exempt from both VAT and the fuel levy, we considered these to be TZS 0.							
Kerosene	2247/litre	615/litre	36.3 MJ/litre	61.9	0.4	**154.75** (0.068)	42.4
Kerosene price: TZS 2247/litre was the EWURA Dar es Salaam price cap for October 2018 (EWURA, 2018b).							
Kerosene duty and levies: TZS 615/litre includes TZS 465/litre in excise duty and TZS 150/litre in petroleum duty (EWURA, 2018b Table 11).							
Electricity	356/kW·h	64.2/kW·h	3.6 MJ/kW·h	98.89	0.7	**141.27** (0.062)	25.5
Electricity price: TZS 356/kW·h is based on the 2018 TANESCO variable tariff (TZS 100/kW·h for the 1st 75 kW·h/month, thereafter TZS 350/kW·h plus VAT (18%) and EWURA (1%) and REA (3%) levies). Given the variable tariff, we calculated the average tariff by assuming that households used 10.74 kW·h per day including 6 kW·h for cooking equivalent to 4 hours of use for 1 average 1.5 kW cooking hob.							
Electricity tax and other levies: TZS 64.2/kW·h is based on an inclusive price of TZS 356/kW·h of which TZS 64.08 is VAT being charged at 18% plus 1% paid towards EWURA and 3% paid towards the Rural Energy Agency.							
Briquettes	1500/kg	229/kg	29 MJ/kg	51.72	0.3	**172.41** (0.075)	26.3
Briquette price: For the energy price comparison, we used the price of TZS 1500/kg. Based on KII with the briquette manufacturer, Mkaa Endelevu, the wholesale price for briquettes in Dar es Salaam was TZS 1000/kg, with most of their retailers selling at TZS 1500. In our survey of retailers, we found that the price of a 2 kg bag ranged from TZS 3000 to TZS 3200 inclusive of VAT.							
Briquette tax: a VAT inclusive price of TZS 1500 equates to a pre-VAT price of TZS 1271/kg with 18% VAT worth TZS 229/kg.							
Ethanol	5900/litre	900/litre	23 MJ/litre	256.52	0.65	**394.65** (0.173)	60.2
Ethanol price: The price of ethanol was recorded from two retailers in Kinondoni. In one retailer, a 1-litre plastic bottle of Moto Poa was sold for TZS 5900/litre. Moto Poa is an ethanol-based fuel imported from South Africa. The fuel was sold alongside camping equipment. In the other retailer, 190g of Hotpack fuel, was sold in tins for TZS 3000. Hotpack is a methanol-based fuel imported from the United Arab Emirates. The packs were sold as chafing fuel alongside catering equipment, for use in buffets. Ethanol was not available in the other 5 shops surveyed. In our price comparison, we have used the price of the cheaper of the two fuels i.e. Moto Poa fuel as this fuel had previously been marketed for household use.							
Ethanol tax: TZS 1500 equates to a pre-VAT price of TZS 1271/kg with 18% VAT worth TZS 229/kg.							

1 US Dollar= 2284 Tanzanian Shillings (TZS), kW·h = kilowatt-hour, MJ = Megajoule.

future, wood and charcoal will be replaced by electric power, gas and petroleum products in line with urbanization of Tanzania' (URT-MEM, 2016b).

Although the 2015 National Energy Policy is consistent with previous policies in its focus on energy transitioning, it differs in taking a more supply-side approach to policy making. While the 1992 and 2003 policies contain sections considering the '*Energy End Use*' (URT, 1992)/'*Energy Demand*' (URT, 2003), there is no equivalent consideration of energy demand in the 2015 policy which is primarily concerned with increasing the supply of, and access to, 'modern' energy sources.

Policy tools that have been used to achieve the energy transition include fiscal tools and charcoal bans. The most significant fiscal tool has been the exemption of LPG from the indirect taxes charged on other imported petroleum products including the fuel levy, excise duty and the petroleum fee. A comparable tax exemption for kerosene, introduced in the 1990s, was reversed in 2011 when excise duty was increased from TZS 52/litre to TZS 400.3/litre with the aim of reducing the price difference between kerosene and petrol which had led to dealers mixing the cheaper kerosene into diesel supplies (UNIDO, 2015).

Since 2006 there have been two attempts to use bans to force consumers to transition away from charcoal. In January 2006, a ban was announced on charcoal production and trade. This was reversed within two weeks following resistance from consumers and traders (Sander et al., 2013). In March 2017, another attempt to prohibit charcoal was made by banning the transportation of charcoal across district boundaries. As with the 2006 ban, the 2017 ban was rapidly reversed and a charcoal task force was established to assess policy options around the charcoal trade.

Comparing energy policy objectives with consumer priorities

The mission of the National Energy Policy of 2015 is '*to provide reliable, affordable, safe, efficient and environment friendly modern energy services to all while ensuring effective participation of Tanzanians in the sector*.' Comparing this with consumer prioritisation of affordability, efficiency and availability, we find that the mission of the national energy policy closely reflects consumer priorities in its focus on affordable, reliable and efficient energy supplies. However, the scope of the policy differs from consumer choices. While 90% of urban households use

Table 4
Price of charcoal sold in units of different volumes.

Unit charcoal sold in	Mean unit price	Price range (min–max)	Mean weight	Weight range (min–max)	Mean price per kg	Price range per kg (min–max)	n
	TZS/unit	TZS/unit	kg/unit	kg/unit	TZS/kg	TZS/kg	
Small plastic bag	1206	500–2000	1.50	0.7–2.60	831	455–1429	17
10-l bucket	2567	1000–4000	3.44	2.8–4.2	755	385–1071	15
20-l bucket	7500	7000–8000	8.00	8.00	938	875–1000	2
Large sack	37,857	24,000–52,000	73.04	47.5–100	561	400–947	7
Overall	N/A	N/A	N/A	N/A	776	385–1429	41

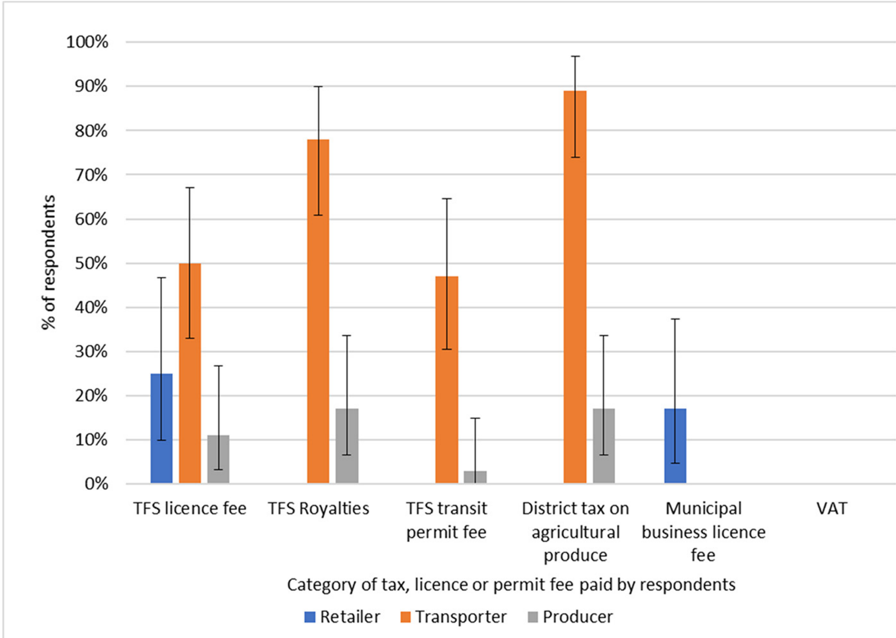


Fig. 7. Fees, taxes and royalties paid by actors along the charcoal value chain with error bars showing the 95% confidence interval.

biomass energy for cooking (charcoal and/or firewood), the scope of the National Energy Policy excludes biomass energy.

Discussion

Is there evidence of an energy transition in Dar es Salaam?

The study shows that there has not been a transition away from biomass energy in Dar es Salaam, over the period of Tanzania's three national energy policies (1992–2015) despite their consistent emphasis on achieving an energy transition. Our work shows that charcoal has remained the most widely used fuel both as the main household fuel, and within a fuel mix. Reduced use of kerosene has largely been matched by increased demand for LPG, with an increase in charcoal comprising households' main fuel between 2001 and 2012 (Fig. 2). Firewood continues to play an important role in more rural municipalities such as Ubungo, while electricity is used occasionally as part of an energy mix. Our results are consistent with previous studies showing that the energy stacking model better describes trends in Dar es Salaam's energy use, than the energy transition model (Choumert et al., 2017).

Total demand for LPG and charcoal have increased and will continue to increase with urbanisation in Tanzania (d'Agostino et al., 2015; Hosier, Mwandosya, & Luhanga, 1993). Dar es Salaam's population increased from 1.3 million in 1990 (Hosier, 1993) to 5.9 million in 2018. In the case of charcoal, if we take the average urban household size of 4.2 people (NBS, 2019), an average household consumption rate of 2.4 kg/day (Hosier & Kipondya, 1993) and 88% of households using charcoal in their household fuel mix, then total annual demand for charcoal in Dar es Salaam has increased from approximately 0.22 million tonnes in 1990 to 0.94 million tonnes in 2018. To achieve a transition in the overall energy mix, the rate of switching from biomass energy to other forms of energy needs to occur at a faster rate than the population growth rate i.e. at a rate > 5.6% per annum. This has profound implications for energy supply planning. Given that a decline in the total volume of demand for charcoal is unlikely, based on the findings of this study and previous studies, there is a need for a policy that will achieve greater social, economic and environmental sustainability around

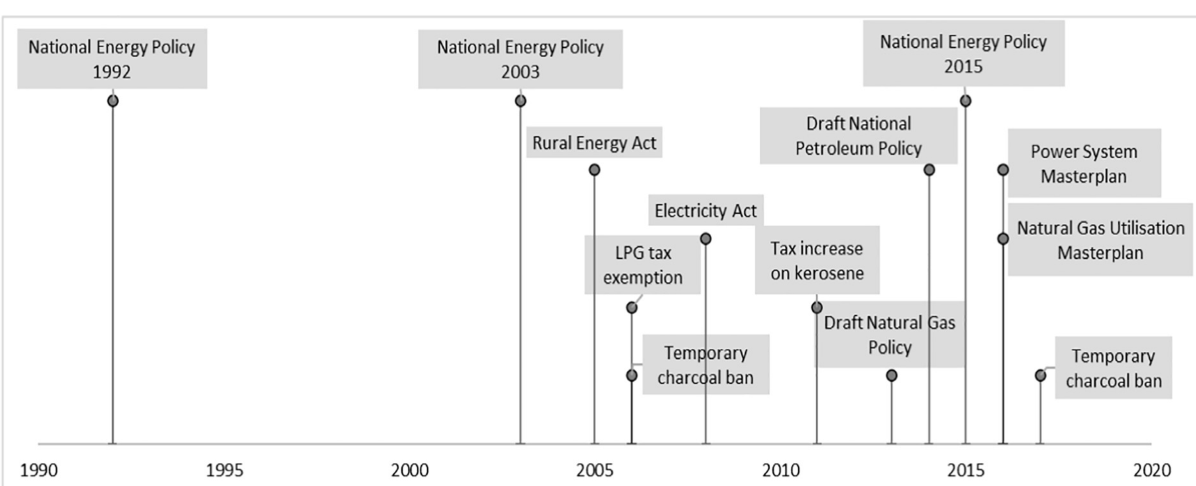


Fig. 8. Timeline of energy policy in Tanzania.

charcoal's role as the dominant source of energy for urban households in Tanzania.

One fuel that was not detected as a household cooking fuel in our surveys is natural gas. Tanzania has substantial offshore gas reserves. The Natural Gas Utilisation Plan includes the strategic objective, '*promoting the use of natural gas as an alternative fuel to liquid fuel, charcoal and wood for domestic use,*' while also stating that, '*the importance of supply of gas as an alternative energy to biomass (mainly charcoal and firewood) makes it necessary for the Government to strategically intervene and promote its implementation through appropriate policies in order to save the fast depleting natural forests*.' The plan assumes that '*10% of households in the country will be supplied with natural gas for cooking by 2045*' (URT-MEM, 2016a). The Tanzania Petroleum Development Corporation (TPDC) is piloting the provision of natural gas to households and industries in Kinondoni Municipality and Mkuranga District (URT-NAO, 2019). For natural gas to contribute significantly to household energy supplies will require the installation of an expensive distribution infrastructure. While its importance is likely to increase in some limited areas where the infrastructure is installed, it seems likely that it will diversify household fuel uses in those areas, rather than transition households away from biomass energy. Thus, while natural gas may play a greater role in decades to come, based on current plans, it is only likely to reach 10% of households, after another two or three 10-year policy cycles. Again, this reinforces the need for a policy relevant to the current situation, while laying a foundation for longer term shifts in Tanzania's energy mix.

Have the policy tools that have been used to influence the urban residential energy sector, achieved the expected policy outcomes, and at what cost?

The influence of LPG tax exemptions and their cost, in revenues foregone

Using fiscal policy tools, Tanzanian energy policies have been effective in influencing demand for kerosene and LPG. The 2011 increase in excise duty on kerosene has contributed to many consumers moving away from kerosene while tax exemptions on LPG have contributed to its growing popularity. This finding is consistent with work showing increased kerosene and electricity use in the 1990s, driven by subsidies (Hosier & Kipondya, 1993). Twenty-five years later, households are still responding to fiscal prompts, albeit away from kerosene and in favour of LPG. While the decline in kerosene use and the increase in LPG use are clear from our household fuel-use data, and fuel import statistics, there is less evidence that these changes have affected charcoal demand given an increase in the proportion of households using charcoal in their mix of fuels (Fig. 3) balanced against a decline in the proportion of households using charcoal as their main fuel (Fig. 2). One reason that LPG is still struggling to compete with charcoal is evident from the results of the fuel-price comparison (Fig. 6). Our results show that, even with the tax exemptions on LPG, LPG is still more expensive per unit of usable energy than charcoal.

The cost of the LPG tax exemptions is high, in terms of government revenues foregone. In 2017/18, 120,961 Metric Tonnes of LPG were imported (EWURA, 2018a). Had taxes been paid on that LPG at a comparable rate to taxes charged on kerosene i.e. TZS 768,750/tonne (based on TZS 615/litre converted at a rate of 1 l = 0.8 kg of kerosene with 1 kg of kerosene being roughly equivalent to 1 kg of LPG in energy content), this would have generated TZS 93 billion equivalent to US$ 40.7 million or 0.74% of the 2017/18 total tax revenue collection of TZS 12.3 trillion (URT, 2018). Using subsidies to encourage LPG adoption also tends to benefit wealthier households and businesses rather than energy poor households (Maes & Verbist, 2012). As an imported commodity, increasing use of LPG will place greater pressure on Tanzania's foreign exchange reserves.

The influence of fiscal policy on charcoal's price

Fiscal policy tools have also boosted charcoal's position in the residential energy market. TRA's decision not to collect VAT on charcoal means that it is effectively exempted from VAT. This contributes to its affordability. Assuming that VAT were charged at 18%, and that the combined retail value of charcoal is TZS 772 billion per annum (0.9 million tonnes @ TZS 776,000/tonne), the effective VAT 'exemption' is worth TZS 139 billion (US$ 61 million) per annum.

A similar pattern emerges in terms of royalties. Although TFS royalties for charcoal are charged at TZS 240/kg, equivalent to 31% of the average price to the consumer (TZS 776/kg), compliance rates may be as low as 10% given the many challenges around revenue collection raised by TFS and other stakeholders, during our interviews. Although 78% of the transporters stated that they pay royalties (Fig. 7), some transporters stated that they only pay royalties on a portion of the charcoal that they transport. Respondents from TFS also suggested that the capture rate is likely to be much lower than 78%. A lower capture rate can also be inferred from a comparison of charcoal consumption estimates and TFS revenue targets. Assuming annual demand for Dar es Salaam of 0.94 million tonnes, the total charcoal royalties for Dar es Salaam alone, should be TZS 226 billion given a TFS royalty rate of TZS 240/kg. Although TFS do not publish disaggregated annual revenue figures from charcoal royalties, the TFS overall revenue target for 2019/20, as announced in the MNRT budget speech, is TZS 153.5 billion, across all forest produce including charcoal, timber and other wood products (URT-MNRT, 2018). Even if charcoal revenues comprise as much as 50% of their total revenue, or TZS 76.7 billion, this would still comprise only one third of the expected value of royalties on charcoal consumed in Dar es Salaam alone. Mwampamba (2007) estimated that the Dar es Salaam charcoal market comprises 30% of the national charcoal market. Thus, while official figures are not available on revenues from charcoal royalties, we can infer from TFS revenue targets and our understanding of the current market size, that the current system of royalty collection only collects a small fraction of the royalties due and that this contributes to charcoal's affordability.

VAT would be an alternative way to collect revenues from charcoal, with the advantage that it is easier to govern charcoal retailers who have fixed premises, compared with transporters who have effectively evaded royalty payments for many decades. Over the last five years, TRA have been effective in broadening the tax base and rolling out electronic fiscal devices to retailers in urban areas. A transition from royalties to VAT on charcoal could build on these successes.

Environmental and health outcomes of the current fiscal policy on LPG and charcoal

While fiscal tools have been effective in promoting more LPG use, this does not equate to achieving policy outcomes around reducing deforestation and pollution. An initial impetus for the exemption of LPG from the fuel levy, was the publication of the report '*The True Cost of Charcoal*', in 2002, by the Tanzania Association of Oil Marketing Companies (Norconsult, 2002). The report argued that charcoal was a major driver of deforestation; that deforestation was costing the country 2% of its GDP; and that subsidising LPG would result in households switching from charcoal to LPG. After 13 years, more data is available to review the assumptions underpinning the decision to exempt LPG from indirect taxes.

We find that three of the key assumptions for exempting LPG from indirect taxes, are not borne out by current research. Firstly, various studies, including our findings, indicate that increased LPG adoption is not equivalent to a transition away from charcoal (Choumert et al., 2017). Research on fuel-switching behaviour indicates that households who adopt LPG rarely switch fuels entirely. Only 10% of households in our survey use LPG without using charcoal. Similarly, work by Alem, Ruhinduka, and Berck (2017) showed that households who adopted LPG maintained charcoal consumption at 75% of pre-LPG, consumption rates. This is linked to the second assumption, that LPG tax exemptions make LPG cheaper than charcoal, whereas the results of the price comparison suggest that, even with the exemptions, LPG is more expensive, on average, than charcoal per unit of usable energy (Fig. 6).

Thirdly, reduced charcoal consumption is not equivalent to reduced deforestation given increasing data showing that agriculture, rather than charcoal, is the main driver of deforestation (Curtis, Slay, Harris, Tyukavina, & Hansen, 2018; Doggart et al., 2020). That fuel subsidies may change households' energy use, but do not result in changes in deforestation was also a conclusion of Hosier and Kipondya (1993), in the context of the kerosene tax exemption.

Similar arguments apply, in terms of public health outcomes being used as a rationale for the LPG tax exemption. If LPG adoption does not equate to reduced charcoal use, then the public health benefits of reducing air pollution, will not be achieved. Even if an impact on public health could be demonstrated, it is unclear that the health outcomes gained by foregoing TZS 93 billion in tax revenues would be the best way to achieve those outcomes, given that the total value of the LPG exemption was equivalent to 54% of the development funds spent nationally on improving health services delivery in 2016/17 (TZS 171 billion) (URT, 2017).

What are the implications for national energy policy of households diversifying rather than transitioning their cooking energy supplies?

The diversification of household cooking energy supplies between 1990 and 2018, has a range of implications for policy and planning. These issues are discussed below, in the order that they appear in the 2015 National Energy Policy:

i. **The vision of the National Energy Policy:** The vision of the policy is of '*a vibrant Energy Sector that contributes significantly to economic growth and improved quality of life of Tanzanians*.' Issues of poverty reduction, employment and economic development are central to the policy's vision. Household energy diversification has profound implications in terms of the energy sector's contribution to economic growth and improved quality of life, that are not considered in the current policy. For example, diversification implies employment and business development opportunities in supplying and trading a wide range of fuels, stoves and other cooking devices.
ii. **The scope of the National Energy Policy:** The tension between the national energy policy and the household energy market arises from the scope of the policy and its roots in the energy transition theory. Based on the energy transition theory, the policy assumes that, if modern energy supplies are provided and urbanisation and development occur, then households will automatically substitute biomass energy with modern energy. From that theoretical basis, the sustainable supply of biomass energy is excluded from the scope of the policy which focuses exclusively on electricity and fossil fuels. In this way the fuel that best meets consumer and energy policy criteria for being reliable and affordable i.e. charcoal, is transformed into 'the fuel to beat' in urban energy planning, using a combination of fiscal and regulatory policy tools. The reason for charcoal's exclusion is rooted in the energy policy mission that energy services should be '*safe and environment-friendly*' combined with policy-makers' deeply held views that charcoal is worse for the environment and public health, than the alternatives (Mwampamba, Ghilardi, Sander, & Chaix, 2013). Another way to approach energy policy development, would be to accept that charcoal is going to be a part of the energy mix for the foreseeable future, and to get behind the development of charcoal to transform it into a modern fuel supplied from well-managed woodlands providing economic development for rural areas; transported in a safe way, providing further employment opportunities; sold to consumers in ways that protect their energy rights; and used by consumers in ways that minimise exposure to pollution and maximise energy efficiency.

Energy transition theory has biased policy-makers away from promoting a more sustainable domestic biomass energy sector and has contributed to a perception of biomass as being an inferior fuel. As concluded by other authors, a policy focus on fuel-switching away from biomass energy '*stands in the way of realistic and effective programs that focus on increasing the sustainability of solid fuel use*' (Maes & Verbist, 2012). This has contributed to policy-makers overlooking the benefits of charcoal including employment creation, energy security, affordability and availability (Owen, 2013).

Households' use of two or more energy forms requires a more holistic policy approach. The policy is currently structured from a supply-side perspective with sections on the electricity sub-sector and the petroleum and gas sub-sector, with policy tools such as sub-sector master plans divided accordingly. Thus, the energy policy is disconnected from the demand side in two ways. Firstly, households are using multiple fuels, as indicated in this study. Plans to improve household energy security require a clear overview of how demand will be met in a way that connects planning for all forms of energy. Secondly, biomass is the primary source of household cooking energy and its exclusion from the national energy policy effectively recuses the Ministry of Energy from responsibility to provide affordable, reliable, sustainable and modern energy for the majority of the present population.

iii. **Capacity building, research and development:** while the current policy focuses on building capacity in the petroleum and electricity sub-sectors, household energy diversification implies the need to include policy objectives that are relevant to charcoal. This might include broadening the curricula in higher education and training institutions around the supply, use and economics of charcoal, as well as investing in training for actors along the charcoal value chain on more energy-efficient, safe and environmentally friendly production methods.
iv. **Integrated planning:** the policy promotes inter- and cross-sectoral planning and the development of sub-sector master plans. While these are highly relevant approaches, in the context of household energy diversification, the effectiveness of these approaches is limited by excluding charcoal. Charcoal requires particular attention to inter-sectoral planning given its relevance to multiple sectors including energy, forestry, land, agriculture, water and environment. Similarly, integrated planning, in the current policy, does not consider the demand side such as linkages with urban planning and the health sector.
v. **Public awareness:** the 2015 National Energy Policy focuses on public awareness on petroleum supply issues including communicating decisions in the petroleum industry and corporate social responsibility of petroleum companies. This excludes awareness on charcoal supply and energy use, including measures that household users can take to improve energy efficiency and reduce exposure to indoor air pollution. Given the primacy of household cooking in overall energy demand, awareness raising on household-level energy efficiency measures, could have profound sectoral impacts.
vi. **Cross-cutting issues of health and environment:** the 2015 National Energy Policy focuses on health and environmental issues associated with the supply of petroleum products and electricity including occupational health and safety and environmental restoration following decommissioning of energy-related installations. Environmental and health issues associated with household energy use and charcoal production are not considered. Again, this is a significant policy gap in the context of household energy diversification.

How can national energy policies be more effective in achieving outcomes compatible with both national priorities and with global goals around climate change and sustainable energy supplies?

Building on the findings from the study, we make four recommendations.

1. Embrace woodfuel, including charcoal, into national energy policy

Achieving household energy security for urban populations in the context of SDG 7, requires an energy policy that guides the sector in matching supply and demand, with special consideration for households facing energy poverty. By excluding biomass energy from the scope of the national energy policy, the policy excludes consideration of measures to improve the supply of up to 80% of the total national energy demand. There are many steps that could be taken to improve the supply and use of biomass energy. On the supply side, interventions are needed to improve regeneration rates and the management of forests supplying charcoal (CHAPOSA, 2002); to improve kiln efficiency, particularly through increasing the skills and working conditions of charcoal producers (van Beukering et al., 2007); and to empower rural communities to benefit from a well-governed and sustainable charcoal production system, including through community-based forest management (Chidumayo & Gumbo, 2013; Maes & Verbist, 2012; Mwampamba, 2007). During transportation, interventions are needed to improve working conditions for charcoal traders including safer vehicles, reduced exposure to charcoal dust, and reducing charcoal waste. For consumers, access to the latest generation of charcoal stoves (Mitchell et al., 2019) and awareness on how to reduce indoor air pollution would reduce health risks and improve efficiency (Das, Jagger, & Yeatts, 2017; Dherani et al., 2008). For example, Maes and Verbist (2012) found that improving ventilation can reduce levels of indoor air pollution from charcoal to levels comparable to LPG stoves. Investing in campaigns to promote safer use of charcoal and to adopt the latest generation of charcoal stoves could bring greater public health benefits than the LPG exemption. These require a policy, resources and a commitment from central and local government to work together to promote a more sustainable, modern supply of biomass energy. Other advantages of embracing biomass energy into national policy include employment, rural development (Schaafsma et al., 2012; Owen, 2013), high local content and reducing pressure on foreign exchange reserves for the import of LPG.

From a climate change perspective, sustainable charcoal production has the potential to reduce net emissions of greenhouse gases from deforestation and forest degradation, thereby contributing to global climate change goals (UNFCCC, 2015). By integrating post-harvesting regeneration of biomass stocks into a sustainable charcoal production system, net emissions are reduced, compared with charcoal production that occurs as part of a transition from forest land to agricultural land (Chidumayo & Gumbo, 2013). Promoting sustainable charcoal production and use is also compatible with Tanzania's Intended Nationally Determined Contributions (INDCs) under the Paris Climate Change Agreement. Tanzania's INDCs include: enhancing efficiency in wood fuel utilisation; enhancing and up-scaling implementation of participatory forest management programmes; and enhancement and conservation of forest carbon stocks (URT, 2015b).

2. Integrate sustainable energy plans into urban planning

Energy planning can be carried out at city level (Ostojic, Bose, Krambeck, Lim, & Zhang, 2013). By calculating projected demand, cities can put in place strategies to ensure a reliable supply of energy, across multiple fuels. Recognising that households are more likely to practice fuel stacking than transitioning, strategies can be put in place to influence households to select a mix of fuels that meet their needs as well as national and global goals around health, environment, local content and other priorities. For Dar es Salaam, we estimate that 17.2 PJ of usable energy will be needed for residential cooking by a population of 11.4 million in 2030, based on current population growth rates. This assumes that the daily requirement of usable energy is 4.14 MJ/person, equivalent to 0.47 kg charcoal (based on 2 kg/household/day reported in Malimbwi & Zahabu, 2008; a household size of 4.2 people; and an energy to pot efficiency for charcoal of 8.7 MJ/kg (Table 3)). This would be equivalent to 6841 GW.h of electricity (see Table 3 for conversion efficiency rates), equivalent to 53% of the 12,870 GW.h total national residential energy demand estimated for 2030 in Tanzania's Power Sector Master Plan, or approximately 0.6 million tonnes of LPG. A sustainable urban energy plan for Dar es Salaam could provide a useful road map, including plans on how to meet the 17.2 PJ of usable energy required for household cooking, by 2030, in ways that balance economic, social and environmental considerations.

3. Evaluate fiscal tools regularly

Our study has shown that fiscal tools have been effective in influencing demand for particular fuels. However, it seems less clear that they have achieved the intended environmental and social outcomes. It is recommended that fiscal tools be re-evaluated regularly and in a more holistic way across multiple fuel-types. It is recommended that the LPG exemption be re-evaluated to examine whether there might be more effective and efficient ways to reduce deforestation and air pollution; and that consideration be given to the implications for Tanzania's foreign exchange reserves, of an increase in dependence on LPG, as an imported commodity. We also recommend evaluating the proposal to replace charcoal royalties with VAT and/or simplifying the system, with a view to increasing compliance rates.

4. Promote fuel efficiency and safer cooking techniques

Promoting energy efficiency measures along the value chain of all fuel types would generate multiple environmental, social and economic benefits (Ouedraogo, 2017, 2019) aligned with national and global priorities. Multiple strategies can be used to achieve this including improved kilns (Mwampamba, 2007) and improved cook-stoves (Bhattacharya & Abdul Salam, 2002; Mitchell et al., 2019).

Further research

With continued urbanisation in Tanzania and other sub-Saharan African countries, there is a need for research into a wide range of topics around sustainable urban energy futures, including on urban energy planning, comparative life cycle analyses for different fuels, and on the economic and social impacts of different energy scenarios for human health, employment and the environment. Given charcoal's continued dominance of the household cooking fuel market, further research around sustainable charcoal production and the role of charcoal production in deforestation, including the connections between charcoal production and agriculture are required. We also recommend that Tanzania's household budget survey add a question to cover all of the cooking fuels that are used by a household, rather than solely focusing on the main cooking fuel, given the prevalence of fuel stacking in urban Tanzania.

Conclusion

In conclusion, fiscal policy tools have been effective in influencing urban households to select LPG rather than kerosene and electricity, for cooking and to diversify fuel use. However, none of the policy tools applied so far, have succeeded in prompting a widespread transition away from charcoal. This is because affordability is a primary concern for consumers and charcoal is cheaper than LPG, electricity and kerosene. Recognising that charcoal's affordability will continue to make it the preferred fuel for many households, a new vision is needed for charcoal that magnifies the positive outcomes of the trade, while mitigating its negative social and environmental impacts.

Declaration of competing interest

None.

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Data availability statement

The data that support the findings of this study are available as supplementary material.

Appendix A. List of policy documents and government reports reviewed

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2020.06.002.

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Chapter 6
Discussion and Conclusions

After a summary of the preceding five chapters, this chapter critically discusses the published material presented in Chapters 3 – 5, linking the findings with the knowledge gaps and research objectives identified in Chapter 1; demonstrating how the three publications advance knowledge; and drawing to the surface the threads that bind the three published works together. This is followed by an assessment of the limitations of the research and recommendations for future research. Potential applications of the research findings for policy and forest management practice, are summarised in recommendations. A concluding paragraph summarises the key 'take-home' messages of the thesis.

6.1 Thesis summary

Chapter 1 Introduction. Understanding rates and drivers of deforestation and regeneration is relevant to national and international efforts to mitigate climate change and conserve biodiversity. In Tanzania, an early transition country with accelerating deforestation, knowledge gaps on deforestation rates and drivers have contributed to ineffective attempts to curb deforestation by restricting charcoal use. Knowledge gaps around regeneration rates, drivers and determinants of biomass and species accumulation, have similarly constrained progress towards sustainable forest management and forest restoration.

Chapter 2 Methods. The thesis primarily comprises quantitative research. A solutions-oriented and interdisciplinary approach is applied. To determine the rates and drivers of deforestation and natural forest regeneration, in Tanzania, the research involved a combination of remote sensing, vegetation plots and structured interviews. The thesis describes an innovative sample-based, time-series remote-sensing method for assessing rates of deforestation and regeneration.

Chapters 3 – 5 comprise three publications. The research records a national deforestation rate of 0.562 Mha y^{-1} (2010-2017), a village land deforestation rate of 0.608 Mha y^{-1} (2011 – 2021) and a village land regeneration rate of 0.013 Mha y^{-1} (1987 – 2021). Small-scale crop cultivation and fallowing are the main drivers of deforestation and regeneration, respectively. Precipitation and time are key determinants of biomass and species accumulation. Given the primacy of agriculture in driving deforestation, and given the ineffectiveness of current policy in changing household charcoal use, Tanzania's energy transition policy has had little impact on deforestation. The thesis presents findings from three original datasets. Findings have relevance for other early forest transition countries, particularly in the miombo belt of eastern and southern Africa. Charcoal policy findings have pan-tropical relevance.

6.2 Deforestation and regeneration rates

The thesis set out to determine deforestation and regeneration rates for Tanzania (Research Objectives 1 and 2), addressing uncertainty around these rates, as set out in Chapter 1.

The thesis demonstrates that, across Tanzania, the gross annual deforestation rate was 1.42% between 2010-2017, or 0.562 Mha ± 0.099 Mha y^{-1}. For village land, the gross annual deforestation rate was 0.95%, or 0.368 Mha y^{-1} (95% CI = 0.308 – 0.432 Mha y^{-1}) averaged over the 34 years between 1987 – 2021 with a baseline 1987 village land forest area of 38.5 Mha. For the final decade of the study (2010-2021), a higher rate of 1.91% (95% CI = 1.46% - 2.46%), or 0.608 Mha y^{-1} (95% CI = 0.46 – 0.78 Mha y^{-1}) is recorded, with a baseline village land forest area of 31.75 Mha in 2010 (95% CI = 29 – 34 Mha). The baseline forest area values are derived from the proportion of village land in the bushland, woodland or forest classes in that year. For the 1987 value, the earliest land cover class recorded per point was used for points with no data for 1987.

In the context of other estimates, the results are closest to the 0.469 Mha y^{-1} (2002-2013) reported in Tanzania's Forest Reference Emission Level (FREL) (United Republic of Tanzania, 2017); higher than the Hansen et al (2013) rate for 2010 – 2020 and the Ortmann et al. (2015) rate; and lower than the McNicol et al. (2018) rate (2007 – 2010) (Table 1 and Figure 3). Other sources have based their rates on the FREL, National Forest Resources Monitoring and Assessment (NAFORMA) and / or Hansen data (Table 1).

By using two independent datasets and analyses, the results give confidence that the national deforestation rate for the last decade is at least as high as the rate indicated in Tanzania's FREL; higher than the rate indicated in the latest Hansen data; but lower than the estimate of McNicol et al. (2018).

The sample-based annual deforestation rate for the 56 Mha of village land (0.608 Mha y^{-1} for 2011 – 2021) is counter-intuitively higher than the rate for the 88.3 Mha of the whole Tanzanian Mainland (0.56 Mha y^{-1} for 2010 – 2017). The higher rate for the village land sub-sample could be due to an acceleration in the deforestation rate between 2018 – 2021, after the national study time period. Alternatively, the sample-based approach may be more sensitive in detecting small-scale deforestation than the wall-to-wall approach of the national study. This latter reason would also explain why the sample-based approach detects more deforestation than using Landsat data (Hansen et al., 2013), unless combined with field-survey data, as in the case of Tanzania's FREL.

Both the national study (Chapter 4) and the study by McNicol et al., (2018) used ALOS-PALSAR data. However, the mean annual deforestation rates of the two studies differed by 0.81 Mha y^{-1}. While it is unclear why the results of the studies vary so markedly, recent papers have highlighted challenges in comparing biomass and forest cover change studies, particularly for African woodlands (Gou et al., 2022; Herold et al., 2019).

The thesis provides new data on Tanzania's regeneration rate relevant for future climate research and reporting. By 2021, 5.6% (95% CI = 4% – 8%) or 3.15 Mha of village land had naturally regenerating forest, including 0.8% ((95% CI = 0.2% – 2%) and 4.8% (95% CI = 3% – 7%) of land that was non-forest and forest in 1987, respectively. The majority of this class (2.7 Mha) is land that has fluctuated from forest to agriculture and back to forest between 1987 and 2021. However, only the 0.8% (0.45 Mha) of land that went from non-forest in 1987 to forest in 2021, comprises a gain in forest cover. Over the

34 y study period, this gives a mean gross annual regeneration rate of 0.0132 Mha y^{-1} (95% CI = 0.0036 – 0.0337 Mha y^{-1}). Comparing this with other studies, the rate reported in Chapter 4 lies between the 0.005 Mha y^{-1} (2000 – 2010) of Ortmann et al., (2015) and the 0.0253 Mha y^{-1} (2000 – 2012) of Hansen et al (2013). Both of their values lie within the 95% confidence interval of the Chapter 4 value, while also noting that their national study areas included forests in protected areas.

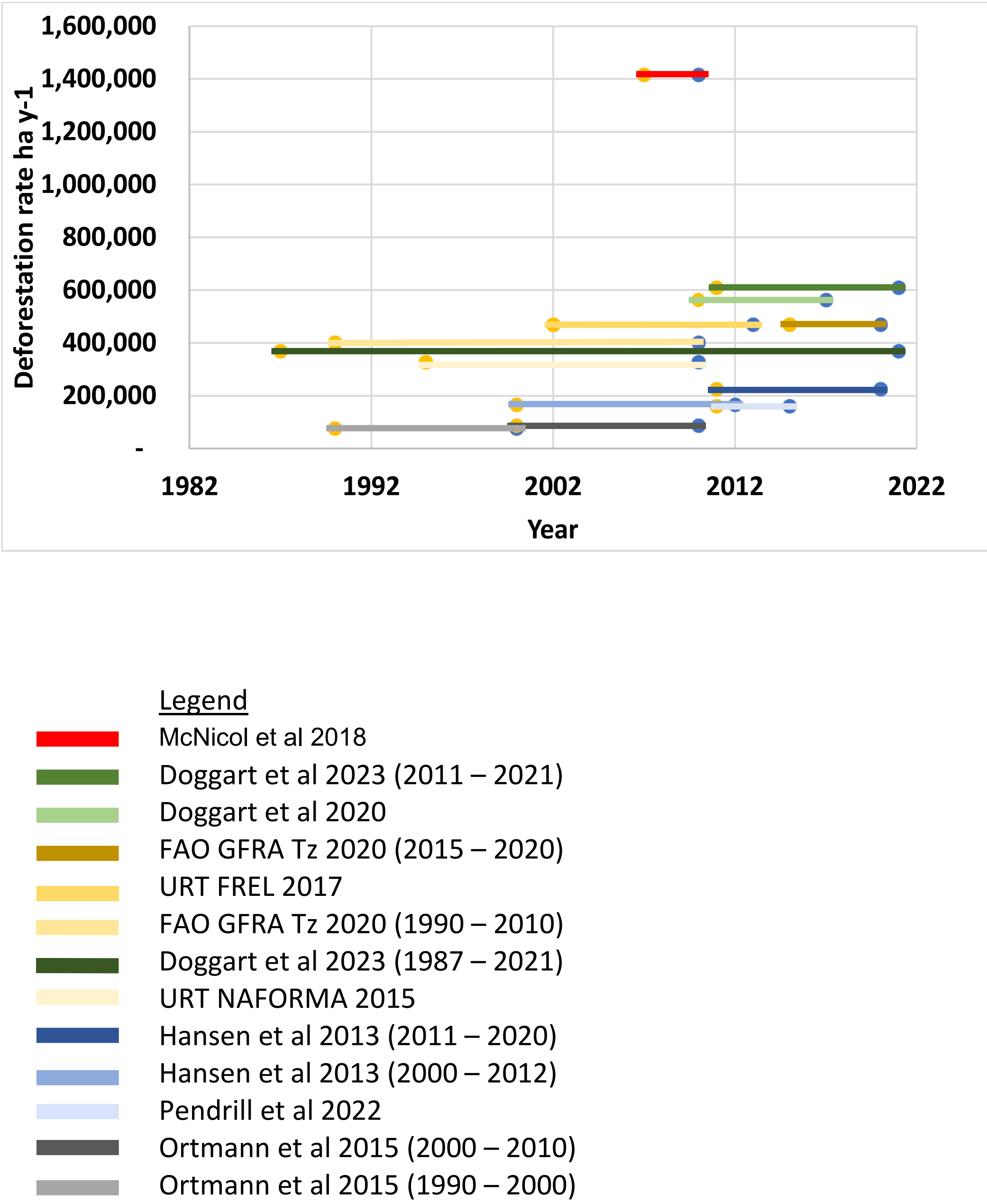

Figure 3 Differences in annual gross deforestation rates reported for Tanzania

See Table 1 for details on the datasets included in the Figure.

Table 1 Published estimates of annual gross deforestation and regeneration in Tanzania

Reference	Time period	Annual mean gross deforestation ha y^{-1}	Annual mean gross regeneration ha y^{-1}	Geographical scope	Forest definition	Source data	Comments
McNicol et al 2018 Table S4b:	2007 - 2010	1,416,400	6,244,745	TZA Mainland	>10 MgC ha^{-1}	Wall-to-wall mapping using PALSAR and 137 field plots in Mz, Tz and Malawi	Area deforested: 4,249,200 ha over 3 years. Area gaining carbon: 18,734,236 ha over 3 years. Excludes areas that were non-forest in 2007 i.e. primarily growth in degraded / low biomass forest areas. Approach: Wall to wall mapping.
Doggart et al 2023	2011 - 2021	607,989	Not included	Village land	TZA definition	Landsat, PALSAR & Sentinel	Approach: Sample based
Doggart et al 2020	2010 - 2017	561,704 ± 99 234	Not included	TZA Mainland	TZA definition	PALSAR	Approach: Wall to wall mapping.
United Republic of Tanzania 2015 FREL Table 4c	2002 - 2013	469,000	Not included	TZA Mainland	TZA definition	Landsat and NAFORMA field surveys	5,159,000 ha over 11 years Approach: Wall to wall mapping.
FAO Forest Resources Assessment TZA Country Report 2020	2015 - 2020	469,420	5,000	TZA Mainland	TZA definition	TZA FREL & NAFORMA	Based on NAFORMA and FREL estimates.

Reference	Time period	Annual mean gross deforestation ha y^{-1}	Annual mean gross regeneration ha y^{-1}	Geographical scope	Forest definition	Source data	Comments
FAO Forest Resources Assessment TZA Country Report 2020	1990 - 2010	400,000	28,000	TZA including ZNZ	TZA definition	Landsat	
Doggart et al 2023	1987 - 2021	367,575	13,246	Village land (61% of TZA Mainland)	TZA definition	Sample-based using Landsat, PALSAR & Sentinel	450,362 ha regeneration over 34 years Approach: Sample based
United Republic of Tanzania 2015 NAFORMA: Main Results. Table 4.16.	1995 - 2010	372,816	See Ortmann	TZA Mainland	TZA definition	Landsat and NAFORMA field surveys	
Hansen et al. 2013 v20200331 from https://globalforestwatch.org/	2011 - 2020	224,372	25,347	TZA including ZNZ	≥10% canopy cover	Landsat	Gross regeneration = 304,169 over 12 years same as 2000 – 2012. Approach: Wall to wall mapping.
Hansen et al. 2013 Table S3	2000 - 2012	165,858	25,347	TZA including ZNZ	≥10% canopy cover	Landsat	Gross deforestation = 1,990,300 ha over 12 years Gross regeneration = 304,169 over 12 years
FAO GFRA 2010	1984-1995	403,329	Not included.	TZA Mainland	TZA definition	Landsat	Approach: Wall to wall mapping.
	2001 - 2010	130,000 – 500,000	Not included.	TZA Mainland	TZA definition	Landsat	Approach: Wall to wall mapping.

Reference	Time period	Annual mean gross deforestation ha y^{-1}	Annual mean gross regeneration ha y^{-1}	Geographical scope	Forest definition	Source data	Comments
Pendrill et al 2022	2011 - 2015	120,000 – 160,00 ha y^{-1}	Not included	TZA including ZNZ	TZA including ZNZ	Landsat	Mainly based on Hansen data.
Ortmann et al 2015	2000 - 2010	86,000	5,000	TZA Mainland	TZA definition	Landsat and NAFORMA	Approach: Sample based
Ortmann et al 2015	1990 - 2000	76,000	8,000	TZA Mainland	TZA definition	Landsat and NAFORMA	Approach: Sample based

As well as providing new empirical evidence on Tanzania's deforestation and regeneration rates, the thesis gives a clearer indication of the direction and extent of *net* change. For village land, we estimate a net loss 12.05 Mha of village land forest between 1987 and 2021 equal to 0.35 Mha y^{-1}. In terms of the spatial distribution of deforestation, the results indicate that most deforestation occurs on village land, reinforcing the findings of Tanzania's FREL (United Republic of Tanzania, 2017). With an accelerating rate of deforestation, the results confirm that Tanzania's deforestation trend is consistent with an early transition country.

6.3 Drivers of deforestation and forest regeneration

6.3.1 Drivers of deforestation

The thesis set out to determine the relative importance of different drivers of deforestation. Chapter 3 demonstrates that crop cultivation is the main driver of deforestation, responsible for 81% of deforestation events. Charcoal was reported to be the main driver for 12% of deforestation events (Figure 4). Typical of other early transition countries, infrastructure and industry are not significant deforestation drivers and were not detected by the study. Co-occurrence of deforestation drivers was reported in 83% of plots, most frequently a combination of crops and livestock (20%).

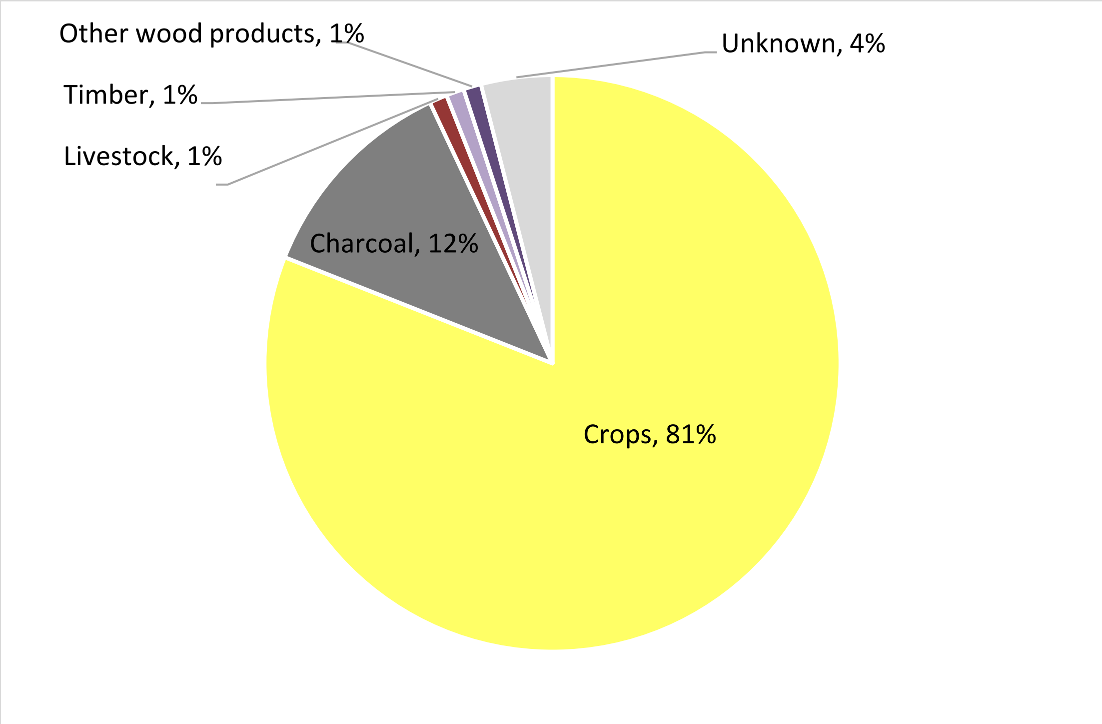

Figure 4 Proportion of deforestation events at which different activities were reported to be the main deforestation driver

Data source: Own data (Chapter 3).

A similar distribution of deforestation drivers is reported in Chapter 4, with crop cultivation as the main driver of deforestation in 86% of plots and charcoal and tree-cutting (not for charcoal) as the main drivers in 6% and 7% of plots respectively. As in the Chapter 3 survey, livestock was reported to be the main driver in just 1% of plots.

The results presented in Chapters 3 and 4 contrast with other studies, particularly in terms of the minimal role of livestock-grazing in driving deforestation. For example, de Sy et al. (2019) reported 14.7% livestock-driven deforestation, in Africa. Similarly, Pendrill et al., (2019) stated that 'cattle meat' drives 27% of deforestation, in Africa. While signs of livestock were reported in 69% of plots in Chapter 3 and 62% of plots in Chapter 4, farmers and other interviewees rarely considered livestock to be the main driver of deforestation. There are several possible reasons for these differences. Firstly, a reliance on remote-sensing, without ground-truthing, makes it difficult to determine the initial cause of deforestation. In studies such as De Sy et al., (2019), an assumption is made that the observed land use caused the deforestation. Under many scenarios this is a valid assumption. However, this can also over-simplify the interactions between different drivers. For example, land cleared for crop cultivation may then be adopted by pastoralists for livestock grazing. This leads to a second reason that previous studies may overstate the role of livestock which is the frequent co-occurrence of livestock and crop cultivation. In Tanzania, livestock grazing and crop cultivation often occur on the same land, either separated temporally or sometimes occurring simultaneously, a source of considerable conflict (Bergius et al., 2020). This contrasts with the design of most analyses of deforestation drivers which are based on single-use land-use classes. These classifications force a choice to be made as to which land-use, the crops or the livestock, to indicate as the deforestation-driving land use. It seems likely that there may be a bias towards classifying land use as livestock rather than crops. This links with a third reason for over-stating livestock which is that the mixed cropping agriculture practiced by many farmers, in Tanzania, can be difficult to distinguish from grazing areas, when relying on remote sensing data. In contrast, cattle watering-holes and enclosures are easier to distinguish. These differences highlight the importance of combining remote sensing with field surveys and of developing deforestation-driver classifications for Africa that better reflect mixed land use practices.

The Chapter 3 results also contrast with other studies in identifying small-scale crop cultivation as the driver of more than three-quarters of deforestation. Most plots (77%) were being farmed for subsistence food production, of which 30% also had a cash-cropping element. Only 12% of plots were for cash-cropping only. In contrast, Hosonuma et al (2012) indicated that, in African early-transition countries, only 42% of deforestation is caused by subsistence agriculture, with 32% caused by commercial agriculture. A similar rate for small-scale agriculture-driven deforestation (35 ± 5%) was recorded in central Mozambique, where pole-cutting, infrastructure and construction played a much greater role (18% of deforestation) (Ryan, Berry, and Joshi, 2014). The thesis results are more similar to Curtis et al., (2018) who estimated that 92% of tree cover loss was driven by shifting cultivation, in Africa. These similarities and differences are likely to reflect definitional differences and variability within

Africa, with Tanzania having a higher proportion of deforestation driven by small-scale agriculture, than other countries. The thesis also provides new data on the types of crop present in deforested areas. 21 crop types were reported. Maize and sesame were the most frequently recorded crops in the areas deforested for crop cultivation (Figure 5). Of the plots in which the two crops were reported, only 1.7% and 29% respectively, were for cash only. The results reinforce other studies' findings that the big-three pan-tropical deforestation commodities (cattle, oil palm and soya bean) are less significant in Africa than in Asia and the Americas. As noted above, cattle only comprised 1% of events, while oil palm was not recorded (although it is grown in a few areas of Tanzania). Beans were reported in 6% of all plots, without distinguishing between soya and other beans. However, they were never produced solely for sale i.e. they were primarily for subsistence use.

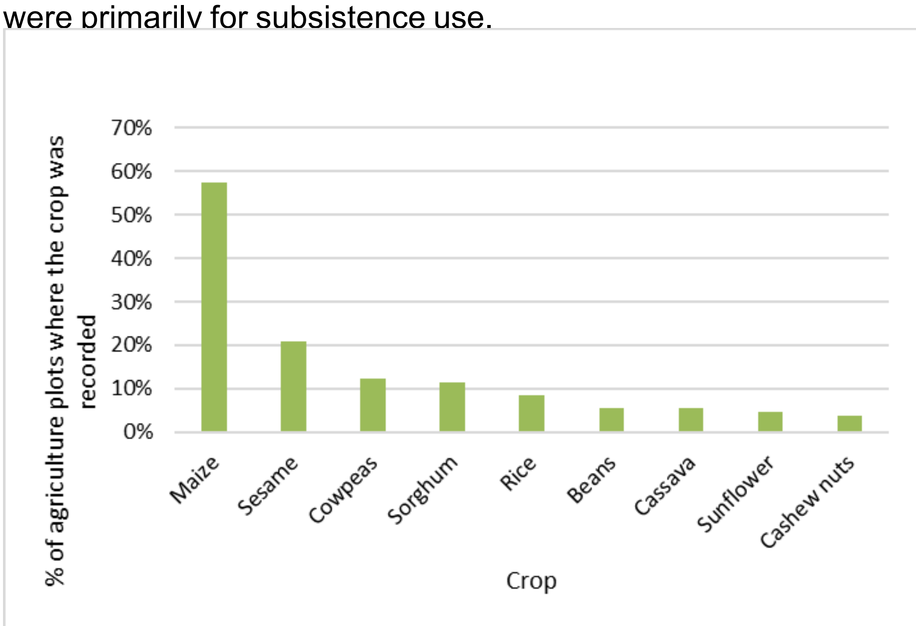

Figure 5 Contribution of different crops to agriculture-driven deforestation

Data source: Own data (Chapter 3).

Charcoal was the main driver of deforestation in 12% and 6% of events respectively for Chapters 3 and 4. The results are similar to the 13±4% recorded in Mozambique by Ryan, Berry, and Joshi (2014) but significantly lower than the Chidumayo and Gumbo, (2013) estimate of 33.16%, which is closer to the overall prevalence of charcoal in deforested areas (35% C. 3). In all cases where charcoal was recorded, crop cultivation and / or livestock grazing were also reported. As in the case of livestock, this points to the inter-connectedness between deforestation drivers, the difficulties in differentiating between main and secondary deforestation drivers, and the variability in motivations for charcoal production, as also reported by Jones et al., (2016).

In summary, the results confirm the primacy of crop cultivation in driving deforestation, with small-scale agriculture as the main driver, in Tanzania. They also demonstrate that charcoal causes far less deforestation than agriculture. Compared with remote-sensing studies, the field survey and interview results provide a more in-depth understanding of the processes driving deforestation, highlighting the complexities of land system change (Meyfroidt et al., 2022). They advance our understanding of the frequency with which drivers co-occur and the potential for bias in attributing deforestation to single drivers, particularly in the overlapping livestock – charcoal - crop cultivation systems that are common in eastern and southern Africa.

6.3.2 Drivers of regeneration

The thesis also set out to determine the relative importance of different drivers of regeneration. Chapter 4 demonstrates that fallowing is the main driver of regeneration, in Tanzania, with 47% of regenerating forest survey plots being used as fallows. The second most common regeneration driver, recorded in 19% of plots, is the abandonment of agricultural land for reasons apart from fallowing. Reasons included out-migration or death of the farmer, and unsuitability of the land for agriculture. The third most common regeneration driver was conservation, found in 18% of plots. The results indicate the importance of shifting cultivation as a regeneration driver, in Tanzania.

Chapter 3 indicates that shifting cultivation is more widespread than the results from Chapter 4 might suggest. In Chapter 3, 28% of all randomly selected deforestation events, from across the country, were fallows. This compares with only 9.6%[1] (5.4 Mha) of village land with regeneration (including long fallows) at some point between 1987 and 2021, as reported in Chapter 4. Fallow length

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[1] Including land cover change classes: AF, AFA, AFAFA, FAFA, FAF, FAFAF where F = Forest and A = Agriculture.

is likely to be the reason for this apparent inconsistency. The short average fallow time practiced by the farmers interviewed in Chapter 3 (2.7 years) means that most fallows did not meet the Chapter 4 criteria for regenerating forest (only one fallow < 3 years old was detected in the Chapter 4 study). In other words, the methods used in Chapter 4 would have missed most fallows (given that, on average, fallows last less than 3 years). While detecting fallows was not the aim of the study, this comparison of the Chapter 3 and 4 results suggests that fallowing / shifting cultivation, is more widespread than Chapter 4 would suggest. For example, if 47%[2] of the RSSPs where regeneration was detected were long-fallows, this would be equivalent to 6% (1.5 Mha) of the 26 Mha[3] of 2021 agricultural land. However, few fallows last long enough to match Tanzania's definition of 'forest' so the total area of shifting cultivation may be closer to 4.5 Mha, or three times the area of long fallow shifting-cultivation, based on the C3 results.

The results in Chapters 3 and 4 provide new insights into the triggers for land to convert from non-forest to forest and point to the potential to integrate longer fallowing in forest restoration efforts.

6.4 Biomass and species accumulation rates in regenerating forests

6.4.1 Biomass and biomass accumulation rates

Chapter 4 presents biomass values of regenerating forest across three vegetation types: bushland, lowland forest and miombo woodland, summarised in Table 4 and Appendix 2.2.3. Chapter 4 shows that biomass values in regenerating woodlands and bushland are at least as high as the national average biomass for those vegetation types. In contrast, for lowland forests,

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[2] Based on Chapter 4 data where regeneration in 47% of FSSPs was driven by fallowing.

[3] Based on C4 dataset indicating that 45% (25.6 Mha) of village land was being cultivated in 2021.

national averages are double those recorded in the survey. Across all vegetation types, refined IPCC values are higher than those reported in Chapter 4 (Rozendaal et al., 2022) (Table 2).

Table 2 Above ground biomass values reported in Chapter 4 compared with NAFORMA and refined IPCC values

Vegetation class (NAFORMA)	Equivalent IPCC Class[a]	Chapter 4	NAFORMA[b,c]	IPCCa
		Mean AGB (SD)		
		Mg ha-1		
Bushland (Open bushland)	African Tropical shrubland	29.3 (26.5)	21.3	48.4 (45.8)
Lowland forest (Lowland forest)	Secondary African tropical moist forest	54.0 (55.8)	92.9	72.8 (36.4)
Miombo woodland (open woodland)	African tropical dry forest	44.1 (19.2)	42.5	69.6 (47.5)

[a] (Rozendaal et al., 2022), [b] (Mauya et al., 2019), [c] applying a 2.13 carbon to biomass conversion coefficient (IPCC, 2006)

Given that all of the Chapter 4 FSSPs had been non-forest at some point over the last 34 years, with a mean regeneration time of only 15 y, and that 96% had one or more degradation driver present, it could be assumed that their AGB would be lower than the values reported by Rozendaal et al., (2022). Even in the case of the Rozendaal secondary moist forest class, although secondary forest, it includes AGB values for plots up to 100 years old i.e. it includes forests much older than those in Chapter 4. The other two IPCC classes include AGB values for all plots in those classes, regardless of successional stage. Therefore, the lower AGB values reported in Chapter 4 when compared with the Rozendaal AGB values, are to be expected,.

In contrast, it is unexpected that the Chapter 4 AGB values for bushland and miombo woodland are higher than national values. One possible reason for this is that there is widespread degradation in these vegetation types, across Tanzania (Nzunda and Yusuph, 2022). Another reason may be an inherent bias in the sampling, whereby post-cultivation regeneration occurs in areas that farmers have selected for agriculture. If farmers select the most productive areas, these are also likely to be the areas where forests grow best.

The Chapter 4 dataset provides an indication of the prevalence of forest degradation, with 2.2% of RSSPs (95% CI: 1.1% – 3.9%) transitioning from a forest or woodland class to the degraded bushland class, without passing through a non-forest class. Assuming some degradation in the additional 5.8% of RSSPs with post-deforestation regeneration, this indicates degradation across at least 7.8% (95% CI: 5.6% – 10.5%) of village land, or 16.6% (95% CI: 12.07% – 21.98%) of village land forest.

Chapter 4 also demonstrates the vigorous capacity for regenerating forests to accumulate biomass and therefore carbon.

The mean biomass accumulation rate was 2.9 Mg ha^{-1} y^{-1}, the same as the biomass accumulation rate for young secondary tropical moist forest reported for Africa (2.9 Mg ha^{-1} y^{-1}) by Requena Suarez et al. (2019). The highest rates were recorded in the miombo woodland plots (3.55 Mg ha^{-1} y^{-1}), similar to rates reported in previous studies of miombo (see Section 1.2.6). The mean biomass accumulation rate for the bushland plots (2.13 Mg ha^{-1} y^{-1}) is higher than the rate reported from bushland in Kenya (1.3 Mg ha^{-1} y^{-1}) (Okello et al., 2001).

The relatively high standard deviation for the bushland class ($\bar{x}$= 2.13 Mg ha^{-1} y^{-1}, σ = 1.78 Mg ha^{-1} y^{-1}, n = 43) indicates high variability. This may reflect the inclusion of ecologically distinct biomes in this class, including areas of fire-dependent savanna, characterised by rapid sapling growth as young trees escape ground-level fire damage (Ratnam et al., 2011).

The biomass accumulation rate was highest in the 6 – 10 y stands (Figure 6), a finding comparable with Kalaba et al. (2013), but earlier than Chidumayo (2013).

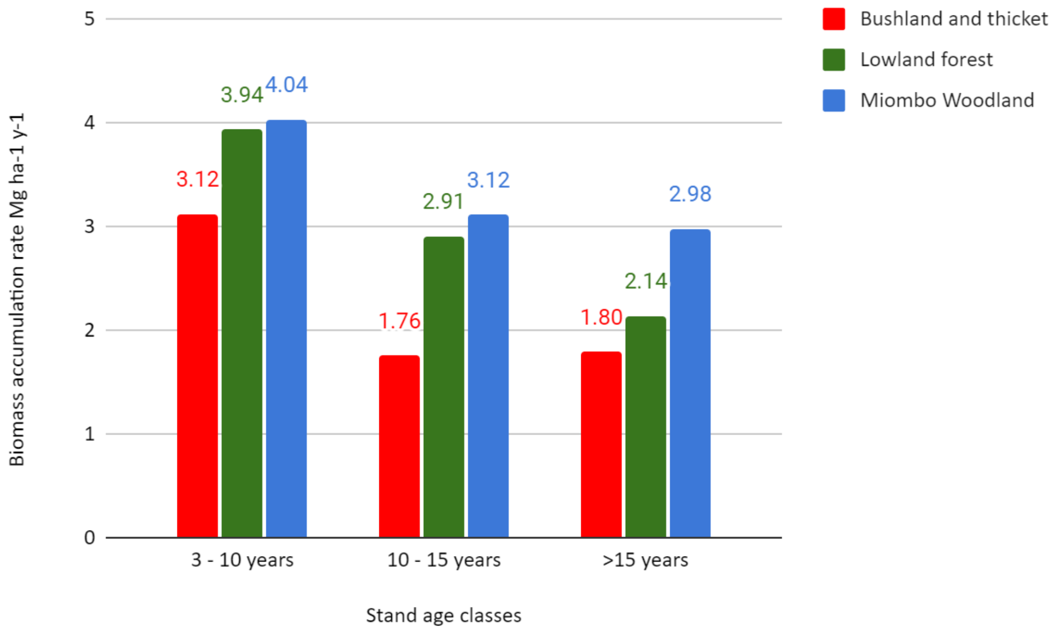

Figure 6 Biomass accumulation rates disaggregated by vegetation type

Data source: Own data (Chapter 4).

In terms of the biomass accumulation rate – stand age relationship, the differences between the findings presented in this thesis and studies in miombo woodland, in Zambia (Chidumayo, 2013; Frost, 1996), point to the variability in regeneration dynamics, with implications for forest management.

Most stems (74.5%) were 5 – 10 cm dbh with stocking densities averaging 4,594 stems ha^{-1}, a higher density than was recorded in 5 – 6 year shifting cultivation fallows in Zambia (1,638 ha^{-1}) (Kalaba et al., 2013) but a quarter of the stem density recorded in regenerating woodlands in Morogoro Region, Tanzania (Njoghomi et al., 2020).

The Chapter 4 biomass and biomass accumulation rates provide new data to understand regeneration dynamics across three vegetation types. It includes data on regeneration in bushland and lowland forest, two under-studied vegetation types.

6.4.2 Factors that affect biomass in regenerating forests

Regeneration time, precipitation, location / district, and the deforestation driver / preceding land use were the variables with the greatest influence on biomass, based on the random forest regression reported in Chapter 4. The relative importance of variables in explaining the above-ground biomass (excluding remnants) across all plots and using three measures of importance from the random forest model, is shown in Figure 7. This highlights the importance of time and precipitation, with location / district and vegetation also showing importance across all three measures of importance. The deforestation driver is important in splitting random forest trees, with less significance using the other two measures of importance.

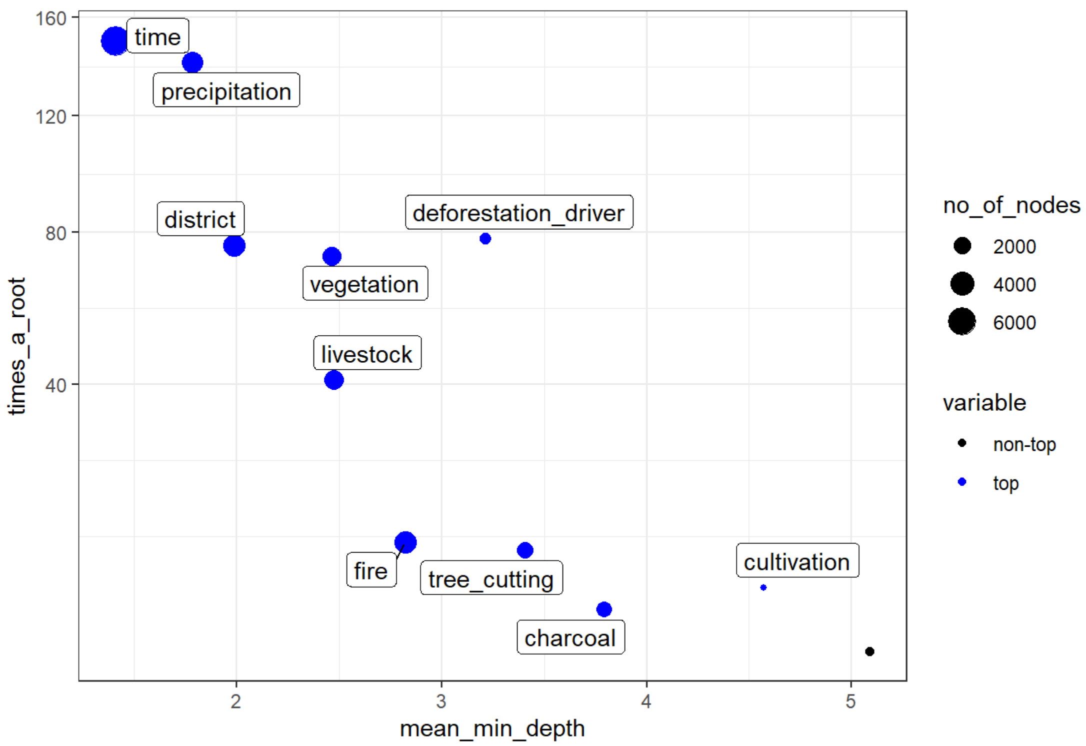

Figure 7 Random forest multi-way importance plot for variables affecting above ground biomass.

Data source: own data (Chapter 4). Prepared using R package 'randomForestExplainer' (Paluszynska et al., 2020). Multi-way importance uses three measures of importance: mean depth of first split on the variable (mean_min_depth), number of trees in which the root is split on the variable (times_a_root), and the total number of nodes in the forest that split on that variable (no_of_nodes). The top ten variables, according to the three measures, are labelled.

The influence of time, precipitation and previous land use reinforces findings by other studies including Jakovac et al., (2021); Moonen et al., (2019) and Mwampamba and Schwartz, (2011). In contrast to other studies, as reviewed by Crouzeilles et al. (2016), livestock-grazing, fire, charcoal production and tree-cutting did not have a strong influence on biomass accumulation.

6.4.3 Species richness and species accumulation rates

Chapter 4 reports an average species richness in regenerating plots that is higher than national average species richness, for the respective vegetation classes. NAFORMA provides data on mean species richness for different forest types (Runsten et al., 2013). The NAFORMA data provide a useful benchmark against which to compare the species richness of regenerating forests. NAFORMA recorded mean tree species richness per plot of: 6 species (maximum = 26 species) for lowland forest, 6 species (maximum = 29 species) for closed woodland, 4 species (maximum = 25 species) for open woodland and 3 species (maximum = 14 species) for dense bushland (Runsten et al., 2013). In contrast, the mean tree species richness per plot reported in Chapter 4 was higher at 13 species (maximum = 27 species), 17 species (maximum = 32 species) and 8 species (maximum = 17 species) respectively for lowland forest, miombo woodland and bushland. Plot size and methodology were the same for NAFORMA and the Chapter 4 study. This comparison between the NAFORMA and Chapter 4 species richness values shows that the species richness reported in Chapter 4 is more than double the national average across all vegetation types. This would suggest that regenerating vegetation has a higher species richness than mature vegetation. However, this conclusion differs from other studies which found comparable levels of species richness in mature miombo and regenerating plots with a stand age of >20 years. When compared with other studies, the values reported by Runsten et al. are unusually low. For example, species richness reported by Montfort et al (2021) for Mozambican miombo woodland plots of 10 m – 16 m radius (compared with our 15 m radius 0.07 ha plots) ranged from '*9 ± 4 species at 4 – 6 years, to 26.4 ± 11.8 species at 30-35 years*.' Similarly, in southern Tanzania, 11 – 20 y, 0.2 ha, regenerating woodland plots had a mean tree species richness of 26 (McNicol et al., 2015). These are closer to the values reported in Chapter 4. Unfortunately, the plot size used in the Zambian studies were larger (0.25 ha) making direct species richness comparisons difficult (Kalaba et al 2013, Chidumayo 2013). The results indicate that tree species richness in regenerating forests can recover to levels comparable with more stable forest areas within a decade.

Across all plots, the mean species accumulation rate was 1.08 species y^{-1}, with the most rapid rate occurring in miombo woodlands. Across all vegetation types, the rate declines with stand age (Figure 8), indicating a non-linear trend, as also reported by Mwampamba and Schwartz (2011).

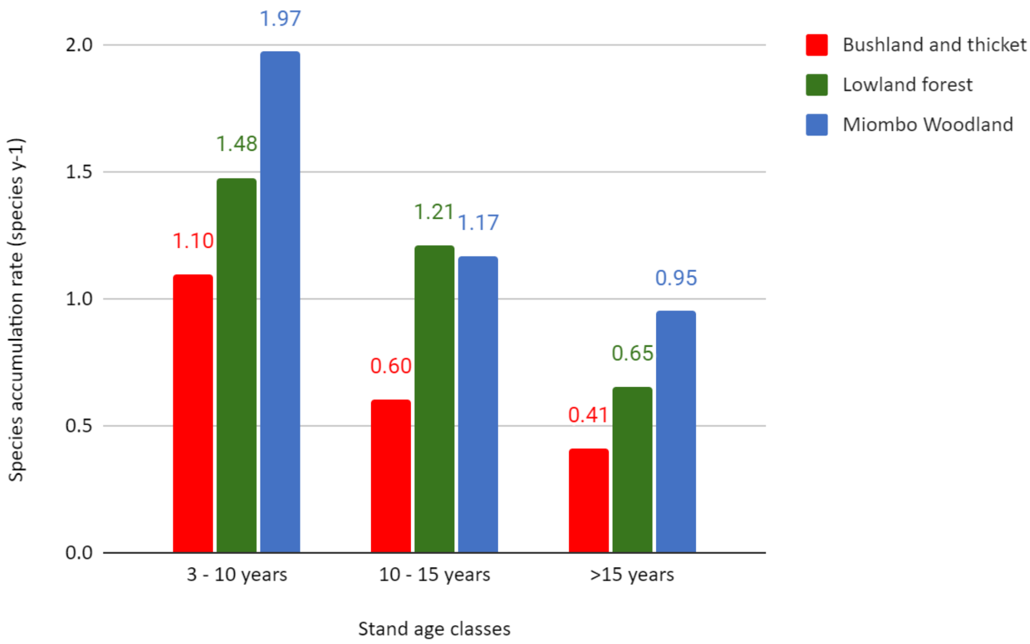

Figure 8 Species accumulation rates disaggregated by vegetation type

Data source: Own data (Chapter 4).

6.4.4 Factors that affect species richness

Location / district, vegetation type, precipitation, livestock grazing, fire and regeneration duration / time were the variables with the greatest influence on species richness, based on the random forest regression reported in Chapter 4. Figure 9 shows the importance of these five variables for the random forest species richness regression model, using three measures of importance.

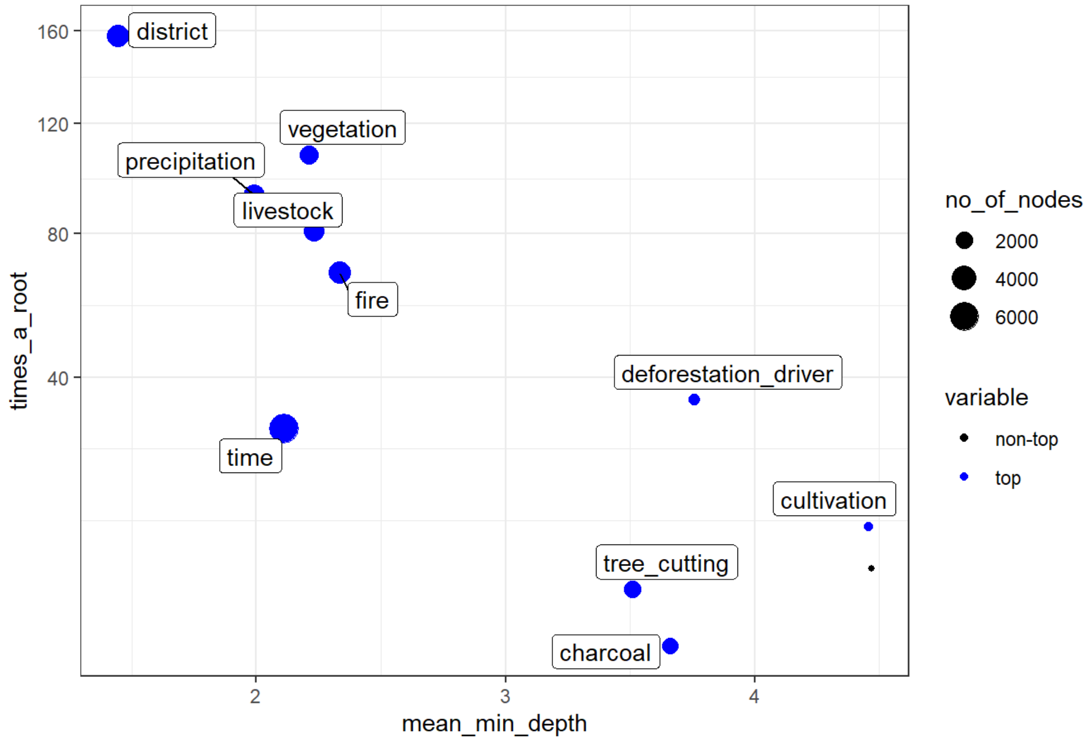

Figure 9 Random forest multi-way importance plot for variables affecting species richness.

Data source: own data (Chapter 4). Prepared using R package 'randomForestExplainer' (Paluszynska et al., 2020). Multi-way importance uses three measures of importance: mean depth of first split on the variable (mean_min_depth), number of trees in which the root is split on the variable (times_a_root), and the total number of nodes in the forest that split on that variable (no_of_nodes). The top ten variables, according to the three measures, are labelled.

Neither the preceding land use, nor disturbances including charcoal production and tree-cutting had a strong influence on species richness. The influencing variables are broadly in line with the review findings of Crouzeilles et al., (2016). However, the low level of influence of the preceding land use differs from findings in localised studies by Moonen et al. (2019) and Mwampamba and Schwartz (2011). This difference may reflect the contrasting scales of the studies such that in the localised studies, where precipitation and vegetation type are more consistent, the influence of land use history is more discernible.

6.4.5 Energy transitioning as a deforestation-reduction strategy

The thesis also set out to investigate the effectiveness of Tanzania's energy policy in reducing deforestation through energy transitioning. Given a national policy of reducing deforestation by limiting charcoal use, Chapter 5 links the new empirical evidence on deforestation drivers (Chapter 3) with new data on charcoal use to examine the impact of the current policy, and policy alternatives. The thesis provides empirical evidence for two reasons why Tanzania's energy transition policy has not achieved its intended goal of reducing deforestation. Firstly, the primacy of agriculture, rather than charcoal, in driving deforestation is demonstrated in Chapter 3. Reducing deforestation requires policy tools that limit the conversion of forests to agricultural land. Secondly, the energy transition policy has not shifted charcoal from its position as the primary cooking fuel, for most urban households. Charcoal's continued popularity, relative to LPG, kerosene and electricity, combined with expanding urban populations mean that charcoal use has increased, in absolute terms, over the last three decades. The energy transition policy has not triggered a reduction in the amount of woody biomass being harvested for charcoal production, as demonstrated in Chapter 5. In addition, empirical evidence on the potential for natural woodlands to sustain charcoal production is provided in Chapter 4. Vigorous regeneration rates, particularly in miombo woodlands, point to the potential to channel that productivity towards biomass energy generation, echoing recommendations from other authors (Jin et al., 2017; Mabele, 2020; Zulu, 2010), while recognising that highly intensive charcoal production can reduce tree and mammal diversity (Tripathi, 2017).

6.5 Research limitations

This section examines limitations of the research. Limitations are defined as challenges and shortcomings that constrain the research outcomes.

6.5.1 Deforestation rates

The thesis adopts a simple definition of deforestation as a transition from forest to non-forest, without setting any minimum time for the land to remain as non-forest after the deforestation event. This was adopted for two reasons. Firstly, setting an arbitrary time limit for land to remain as non-forest created challenges equal to not setting a time limit, particularly given known variability in shifting cultivation fallow-length. Secondly, the definition was more appropriate to investigating the role of charcoal in deforestation. However, it limits the comparability of the results with other studies which classify forest clearance events caused by charcoal, timber and pole-cutting as degradation events. In particular, it limits comparisons with the widely-cited paper, Hosonuma et al. 2012. In addition, it meant that by the time the Chapter 3 field surveys were conducted, some plots were already regenerating to forest, limiting observations of the deforestation-causing activity.

6.5.2 Differences in the sampling strategy and study area between Chapters 3 and 4

The two deforestation driver datasets, as presented in Chapters 3 and 4, are not directly comparable because of significant differences in the sampling strategies and study area. Firstly, the study area for Chapter 3 is the whole of Mainland Tanzania, while Chapter 4 is limited to village land. Secondly, Chapter 3 applied a random sampling approach across all deforested land, while Chapter 4 uses a clustered sampling strategy for the FSSP data on regeneration drivers, biomass and species richness.

6.5.3 Sample size and study area

Sample sizes for all three studies were limited by time and other resources. While the confidence intervals for the surveys are in line with many other studies, some rare classes were not detected. For example, infrastructure and urbanisation were not detected as deforestation drivers despite known examples of infrastructure developments causing deforestation, in Tanzania. Similarly, in Chapter 4, regeneration as a transfer from non-forest in 1987 to forest in 2021 was only detected in 4 of the 500 sample points, limiting deeper analyses. The study area for Objective 1 in Chapter 4 excluded evergreen forests and grassland, on village land. The rationale for excluding natural grasslands was that they were stable areas irrelevant to the research question. By excluding them, time could be allocated to the habitats relevant to forest cover change dynamics. The rationale for excluding evergreen forests was that they were inappropriate for charcoal production given their ecological sensitivity compared with miombo woodland’s tolerance for moderate disturbance (Frost, 1996; Tripathi, 2017). Since, the initial rationale for the study was to understand how natural regeneration could be integrated into woodland management that integrates sustainable charcoal, this was consistent with that research interest. However, it means that 0.6 Mha or 2% of the 2010 village land forest area, are excluded.

6.6 Recommendations for further research

6.6.1 Shifting cultivation

Further research on the net climate, biodiversity and livelihood benefit of promoting long-fallows in agricultural policy tools, is needed. Small-scale agriculture, including shifting cultivation, is the main driver of deforestation and regeneration, in Tanzania, as reported in Chapters 3 and 4. The thesis also demonstrates that shifting cultivation fallows rapidly accumulate carbon and biodiversity values. While Heinimann et al., (2017) point to a global decline in shifting cultivation, there is uncertainty around how and why practices are changing, including in terms of geographical extent and fallow length (van Vliet et al., 2012). However, trade-offs between livelihood resilience, incomes, agricultural yields, ecosystem services and access to forest products that are inherent in decision-making on fallow length, crop combinations, field selection and other aspects of shifting cultivation, remain poorly understood (Kilawe et al., 2018; Llopis et al., 2019; Mertz, 2002; Zaehringer et al., 2017). This links with broader debates around land-sharing and land-sparing and the future of fallows in the agricultural landscape (Balmford et al., 2018; Kremen, 2015; Mertz and Mertens, 2017; Van Vliet et al., 2013). It has implications for agricultural and forest policy.

6.6.2 Policy measures to reduce deforestation

For early transition countries, such as Tanzania, there is still uncertainty about which policies are effective in reducing deforestation (Seymour and Harris, 2019). In particular, policy-related challenges remain as to how to balance trade-offs between reducing net deforestation and policy goals in the agriculture, energy and forest sectors (Melo et al., 2020). While Chapter 5 demonstrates the ineffectiveness of relying on an energy transition policy to reduce deforestation, it does not answer the question of what policies *are* effective. A comparative review of the agriculture – forest – energy policy nexus in countries with different forest transition trends could provide valuable, solution-oriented insights.

6.6.3 Co-occurring deforestation drivers

More research is needed on the complex mix of drivers that differentiates deforestation in Africa, from other parts of the world (Fisher, 2010). Chapters 3 and 4 demonstrate widespread co-occurrence of two or more deforestation and / or degradation drivers, most commonly crops and livestock. Interaction between co-occurring drivers affects the livelihood, biodiversity and climate impact of deforestation events (Mwampamba et al., 2018). Since most studies focus on the main driver of deforestation, the impact on regeneration dynamics, climate and biodiversity of these co-occurring activities has not been well-documented (Manyanda et al., 2021). More broadly, research on the nexus between land, livestock, crops, energy and forests is needed.

6.6.4 Sustainable charcoal production

More research is needed to support change in the charcoal trade, with the aim of improving the trade's environmental, health and governance outcomes. Chapter 4 provides new data on regeneration rates in different vegetation types, and indicates the variables affecting biomass accumulation rates. This is useful in forest management planning including for areas designated for sustainable charcoal production. However, more research is needed on optimal harvesting practices, including harvesting rotations. As indicated in Section 1.2.6, a wide range of optimal stem diameters, for charcoal production are proposed (FAO, 1983, 2017; Syampungani et al., 2010). Chapter 4 suggests that stem diameter may be a more important determinant of the harvesting rotation, than overall biomass. Other management techniques such as thinning, selective harvesting and fire management have also been proposed for miombo woodland charcoal production (Chidumayo et al., 1996). Chapter 4 also highlights the variability in biomass accumulation, particularly in the bushland class. More research is needed on best practices for natural forest management and wood-harvesting for sustainable charcoal, including in bushland. Building on the policy issues highlighted in Chapter 5, solutions-oriented research is needed on how to enhance the positive outcomes of the charcoal trade, while mitigating negative impacts on environment, health and governance (Branch et al., 2022).

6.6.5 Regeneration and deforestation rates in other areas

Chapter 4 presents an innovative approach to assessing regeneration and deforestation rates. The method can be applied at different scales and for any country. Given Google Earth Engine's provision of free, online access to multiple remote sensing datasets, the approach is a cost-effective option for countries or regions interested in determining deforestation and regeneration rates. For Tanzania, scaling up the study to a national study would add value. By updating the results, using the latest data in Google Earth Engine, the dataset can be used for forest cover change monitoring. Chapter 4 also highlights the need for more research on regeneration dynamics in bushlands, an area of 0.9 Mha in Tanzania (United Republic of Tanzania Ministry of Natural Resources and Tourism, 2015). Disentangling this vegetation class and its dynamics is particularly important in the context of forest restoration initiatives. Afforestation of savanna habitats risks damage to the unique fire-dependent savanna ecology (Veldman et al., 2015).

6.7 Implications for policy and forest management

6.7.1 Policy

Energy - In terms of energy policy, the key recommendation of the thesis is to embrace charcoal as an affordable, available, homegrown energy supply, while mitigating its negative impacts on health and the environment. This is because charcoal is a reliable, accessible and affordable product that meets households' basic need for cooking fuel. It is sourced from extensive natural woodlands that regenerate rapidly after harvesting. These characteristics render charcoal's supply and demand resilient to government interventions to reduce use through legislation or fiscal tools (Chapter 5). Numerous measures could be taken to mitigate charcoal's impact on health, governance and the environment. This requires charcoal's pariah status to be removed (Mabele, 2020). An 'energy transition' from charcoal to LPG will have little effect on the national deforestation rate, since charcoal does not drive most deforestation (Chapter

3). As such, conserving forests through subsidies and tax breaks on LPG is ill-advised (Chapter 5).

In Tanzania, in 2022, the Ministry for Natural Resources and Tourism finalised the draft National Charcoal Strategy, following five years of research, consultation and planning (United Republic of Tanzania, 2019). The draft strategy embraces sustainable charcoal production and includes measures to improve charcoal trade and use. However, at the time of finalising this thesis (December 2022), the strategy had been put on hold following statements by the President of Tanzania, in November 2022, to end the use of charcoal in favour of LPG and other 'clean cooking fuels'[4]. It is recommended that the National Charcoal Strategy be revived. The strategy is a step towards a more holistic energy strategy that embraces reform in the charcoal sub-sector. This is compatible with simultaneous promotion of LPG, as demonstrated in Chapter 5. This dual track approach requires more inter-sectoral coordination between the energy and natural resources sectors, as recognised by the current Minister for Energy, January Makamba[5].

Given the resilience of the charcoal market, proceeding with reforms to improve the governance, environmental and health outcomes related to charcoal, remains compatible with the energy policy mission of providing *'reliable, affordable, safe, efficient and environment friendly modern energy services*' (United Republic of Tanzania, 2015). The research presented in this thesis

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[4] *'Tanzanian President Samia Suluhu Hassan… directed authorities to form a national task force of experts that will make a roadmap for promoting the use of clean energy for cooking. …, that will help end the use of charcoal and firewood for cooking which caused environmental destruction and health hazards.'*

https://english.news.cn/20221102/ad7f285f457b433ca4a0f87cf556997e/c.html

[5] ' *"We are seeing the necessity for intervention now, given the trends," says the energy minister, January Makamba, adding that his ministry (Energy) and the forestry department will need to better coordinate their work to find alternative sources of income – which won't be easy.*'

https://www.theguardian.com/global-development/2022/dec/13/tanzania-charcoal-trade-deforestation supports the revival of the charcoal strategy and other measures to reform the charcoal sub-sector. These issues are described in further detail in Appendix 4.

Forest – the thesis highlights the rapid net loss of forest area, particularly on village land. Measures to address deforestation are urgently needed if Tanzania is to maintain forest on village land. Land sparing approaches, particularly increasing the number and size of community-owned village land forest reserves, are recommended. Land sharing approaches, integrating forest patches into the agricultural landscape, are also recommended. Long-fallow shifting cultivation promotes a mosaic of land covers that include forest patches with attendant biodiversity and other forest ecosystem services.

A land sparing approach that conserves forests in village land forest reserves is reflected in the National Community-Based Forest Management (CBFM) Action Plan, published in 2022, by the Ministry for Natural Resources and Tourism (United Republic of Tanzania, 2022). The plan includes targets to scale-up CBFM as a way to sustain natural forest on village land. The plan includes the integration of sustainable forest-product harvesting, including charcoal, in CBFM areas. Political and financial support for the implementation of this plan, are needed.

Implications for policy for Chapters 3 and 4 are summarised in the policy briefs presented in Appendix 4. These have been widely circulated in Tanzania, including in processes linked to the development of the National CBFM Action Plan and draft National Charcoal Strategy.

6.7.2 Forest management

Given rapid biomass accumulation rates in miombo woodlands, Chapter 4 demonstrates the potential for natural regeneration to be used as a forest restoration tool, supporting the findings of other studies including Crouzeilles et al., (2016); Lewis et al., (2019); and Shimamoto et al., (2018). This links with targets in the National Forest Policy Implementation Strategy to restore 5.2 Mha of forest by 2030 (United Republic of Tanzania Ministry of Natural Resources and Tourism, 2021).

In terms of sustainable harvesting, Chapter 4 indicates the potential to manage natural woodland and bushland for charcoal and timber. The research provides new insights on the challenging issue of harvesting rotations. Chapter 4 suggests that the maximum annual increment in biomass is reached between 6 – 10 years in miombo woodland. However, the results also indicate that stem size may only reach 3 – 5 cm dbh at 6 – 10 years with some references indicating that this is sub-optimal for charcoal production. Therefore, Chapter 4 provides new evidence supporting current harvesting rotations of ≥15 years, while indicating the need for more research for shorter rotations (see 6.6.4).

The research indicates that regenerating forests could contribute significantly to overall charcoal demand. Taking an estimated national charcoal demand of 2.3 Tg y^{-1}, and an estimated 8.4 Mha of woodland needed to produce this sustainably (assuming aa 24-y rotation), the 3.15 Mha of regenerating woodland could supply ~ 38% of demand (Doggart and Meshack, 2017). Alternatively, if the 4.3 Tg C y-1 sequestered in regenerating village land forests were converted to charcoal, it is equivalent to 1.7 Tg of charcoal[6], or 74% of estimated demand. These are very rough estimates and it is not proposed that all regenerating forests be used for charcoal. However, they give an indication of the potential contribution that regenerating forests on village land could make towards national energy supplies.

6.8 Conclusion

The thesis set out to determine rates and drivers of deforestation and natural forest regeneration, in Tanzania, the fifth highest deforestation country globally. The gross mean annual deforestation rate for mainland Tanzania was 0.56 Mha y^{-1} (2010 – 2017), confirming that Tanzania remains a global deforestation hotspot. Focusing in on the 56 Mha of community-owned (village) land, the gross mean annual deforestation rate was 0.368 Mha y^{-1} (1987 – 2021)

[6] The 4.3 Tg C y-1 estimated to sequestered on village land (Chapter 4) can be converted to 9.15 Tg biomass y-1 using a 0.47 carbon : biomass conversion factor. Assuming a 19% biomass to charcoal conversion efficiency (see (Doggart and Meshack, 2017)

accelerating to 0.608 Mha y^{-1} in the final decade of the study (2011 – 2021). This indicates that Tanzania's most threatened forests are on village land and that the threat to those forests is increasing. This has profound implications for the livelihood resilience of the millions of people dependent on village land forests for food and wood products, as well as for the forests' biodiversity and climate values.

The gross mean annual regeneration rate on village land was 0.0132 Mha y^{-1} (1987 – 2021). The village land natural forest regeneration rate has not been measured before and this is a key finding of the thesis. By understanding this figure, the net change in forest area can be calculated giving a net mean annual rate of forest loss of 0.354 Mha y^{-1} (1987 – 2021), demonstrating that far more forest is being cleared than is re-growing.

Although the area of land that has regenerated from non-forest to forest between 1987 and 2021 is only 0.45 Mha, a much more extensive area of land, 2.7 Mha, has fluctuated from forest to agriculture and back to forest. With a mean annual biomass accumulation rate of 1.4 Mg C ha^{-1} y^{-1}, this equates to a carbon sequestration rate of 4.3 Tg C y^{-1} over the 3.15 Mha of regenerating land, offsetting 36% of Tanzania's deforestation emissions. This demonstrates the important role of regenerating village land forests in Tanzania's carbon balance, a value not yet reflected in Tanzania's carbon accounting.

The thesis demonstrates that the main driver of deforestation is small-scale crop cultivation (81%). Charcoal causes 12% of deforestation. Livestock causes 1% of deforestation, less than other published estimates. Shifting cultivation fallows are the main driver of regeneration, followed by abandonment of agricultural land and conservation. That agriculture is both the main driver of both deforestation and of regeneration highlights the importance of involving the agriculture sector in action to address Tanzania's accelerating net forest loss. Instead, however, the thesis describes a deforestation-reduction policy that has focused on promoting a transition in household cooking-fuel use away from charcoal. As well as focusing on a minor deforestation driver, the thesis demonstrates that the policy has done little to reduce charcoal's popularity and widespread use.

Policy developments in 2021/22 supporting community-based forest management and sustainable charcoal production, may signal a change in direction. Given rapid net deforestation, action in the next 10 – 20 years will be critical, if Tanzania is to flatten and nudge its forest transition curve upwards.

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Appendix 1 Supplementary material for Chapter 3

Supplementary material for the publication ‘Agriculture is the main driver of deforestation in Tanzania.’

Also available at: https://iopscience.iop.org/article/10.1088/1748-9326/ab6b35

Appendix 1.1 Methods

Definitions

Our classification of deforestation drivers broadly follows Hosonuma et al (2012) with the exceptions that we considered all types of settlement, rather than just urbanisation, and we did not distinguish between commercial and subsistence agriculture.

Mapping Deforestation

We used the freely available Global PALSAR-2/PALSAR/JERS-1 Mosaic product provided by JAXA (Shimada et al 2014) together with the NAFORMA Land-use / Land-cover (LULC) Map 2010 (URT - MNRT 2015) to map forest cover for all of the Tanzania mainland in 2010 and gross deforestation from 2010 to 2017. The JAXA PALSAR data are orthorectified, slope corrected backscattering coefficients for HH and HV polarizations. The data comes in a latitude / longitude grid using the WGS84 datum. Pixel sizes near the equator are approximately 25 m x 25 m. For this analysis, only the HV polarization was used as previous experience and other studies had shown HV polarization having the most consistent relationship with woody biomass (Mitchard et al 2009).

A Lee filter (Lee 1983) was applied to all HV backscatter data to reduce speckle. Then, to reduce the influence of uneven rain and soil moisture patterns due to the differences in times of year in which the mosaic data was gathered, a composite of the lowest pixel values for 2007-2010 was generated. The composite mosaic was then displayed over high-resolution imagery on Google Earth in various parts of the country. Different thresholds were applied to identify the cut-off between forest and non-forest, with Digital Number (DN) value ≥ 2100 resulting in the most accurate forest map for the country. Forest was identified as per the Tanzanian definition submitted to the UNFCCC – areas of at least 0.5 ha with greater than 10% canopy cover of trees at least 3 meters in height. This process also revealed a small consistent geolocation shift in PALSAR data compared to imagery on Google Earth. The PALSAR mosaic was shifted to line up with Google Earth.

Previous experience using PALSAR data to map forests in Tanzania showed that it was likely to falsely identify dense wetland vegetation, some dense settlement areas, and steep grassy slopes as forest. To reduce these errors, we identified polygons from the NAFORMA LULC Map 2010 that were mapped as settlement, flood plain, flooded cropland, or cropland or grass in areas of steep slopes. These areas were reclassified as non-forest in the forest / non-forest map generated from the threshold of HV backscatter data.

Deforestation from 2010 to 2017 was then mapped based on four criteria. The area had to be mapped as forest in 2010, below the DN threshold for forest in 2015, 2016, or 2017, show a relative decline in HV backscatter of at least 15% compared to the lowest value in the 2007-2010 composite mosaic, and be orthogonally connected to at least 5 other pixels of deforestation equivalent to 0.375 ha. We adopted a 6-pixel threshold for deforestation to maximise user accuracy whilst still being able to detect small-scale deforestation events.

The accuracy of each of the map classes (non-forest, forest persistence, and deforestation) was assessed by one author (TB) visually reviewing Landsat, Sentinel-2, and Google Earth imagery for a random stratified sample of 300 pixels in each map class. A stratified sample was used in order to increase the sample size of the deforestation samples since it was a rare class and the focus of the study. An independent assessment of roughly 100 points from each map class was conducted by another author (ND) with 98% agreement with TB's assessment.

The assessment was carried out using Google Earth, Google Earth Engine and QGIS. An earth engine script was prepared to overlay Sentinel 2 and Landsat images from 2009/2010 and from 2015/16 and 17. PALSAR and Google earth images were also displayed (See Annex 1). A bounding box was used to mark the pixel being assessed. Results of the assessment were recorded in the QGIS sample point attribute table. At the start of assessing each point, the point was viewed in Google Earth using the kml file. If high resolution imagery was not available covering the timespan of the study, then the sample point was examined using the images opened in Earth Engine. The earth engine script was run and imagery from different sensors and dates were then visually reviewed. Each sample point was then classified as 0 = Non-Forest or 1 = Forest remaining Forest, or 2 = Forest becoming Non-Forest. A confidence score from 0 – 2 was indicated for each point. Detailed notes were recorded to justify the classification of each point and information on the availability of high-res images and Sentinel 2 images at the start and end of the study period were recorded. For a point to be classified as forest becoming non-forest, it was required that change affect the pixel plus at least 5 additional pixels, orthogonally connected with the sample pixel i.e. covering an area of at least 0.375 ha with at least 10% canopy cover. In a situation where only the sample pixel changed from forest to non-forest, this was not considered to be a deforestation event. The accuracy assessment followed that described in Olofsson et al (2013, 2014), where the error matrix is presented as estimates of area proportions, in order to account for the stratified sampling design. The accuracy results and error matrix are presented in Supplementary Table 1.

Supplementary Table 1 Estimated error matrix with cell entries expressed as the estimated proportion of area

Map categories are rows while the reference categories are columns: 1 = non-forest, 2 = forest persistence, 3 = deforestation.

Class	**Estimated area proportion**				**Accuracy assessment score**		
	1	2	3	Total	User's accuracy	Producer's accuracy	Overall accuracy
1	0.549	0.048	0	0.597	0.92	0.97	0.92
2	0.015	0.342	0.011	0.368	0.93	0.87	
3	0.002	0.002	0.030	0.034	0.87	0.73	
Total	0.566	0.393	0.041	1.000			

Supplementary Table 2 shows the mapped areas of each class and the estimated areas based on the reference data with 95% confidence intervals.

The reference-based area estimates and confidence intervals are calculated as per Olofsson *et al* (2013).

Supplementary Table 2 Class area estimates in hectares

Class	Mapped Area (ha)	Reference Data Area Estimate with 95% Confidence Interval (ha)
Non-Forest	57,268,962	54,263,241 ± 1,940,328
Forest Persistence	35,319,374	37,678,247 ± 2,047,955
Deforestation	3,294,080	3,931,927 ± 694,665

The mapped annual deforestation area was equivalent to 470,581 ha yr^{-1}, while the reference data area estimate was 561,704 ha yr^{-1} ± 99,238 ha yr^{-1}. Using the approach in Puyravaud (2003), the gross annual deforestation rate for the mapped deforestation area was 1.27% while the estimate based on reference data was 1.42%.

Ground surveys

The geographical scope of the study included Mainland Tanzania and Zanzibar. However, none of the randomly selected ground survey points fell in Zanzibar.

The survey aimed to include at least 97 sample points. This is based on a 10% margin of error at a 0.95 confidence level where P = 0.5. This gives a minimum sample size of 97. An additional 23 points were included in the survey in case some of the sample points could not be reached in the field, or in case some points turned out to have been mis-classified. One ground survey point in a village land forest reserve was found to be a mis-classification. Although some clearance for agriculture had occurred in the mis-classified plot, the clearance had been stopped by the village authorities before it reached the threshold to be classified as non-forest. Data from this plot has not been included in the analysis. Ground survey points were included in the study where there was evidence that the plot had been non-forest at some point between 2015 – 2017. In some cases, the plots had started regenerating even prior to 2015 but still met the non-forest criteria by 2015. By 2018, 10% of survey points met the ‘forest’ class criteria of having a canopy height of > 3 m and a canopy cover of 10% - 40%, while 90% of plots had a canopy cover of less than 10%. Plots that met the ‘forest’ class criteria by 2018 were still included in the study since the temporal scope of the study was 2010 – 17.

We used road data from OpenStreetMaps, and hand digitized roads and paths from Google Earth and Sentinel-2 imagery, to generate mobile-navigation maps for each point. The team was equipped with bluetooth GPS devices accurate to 3 metres.

Informant Interviews

Where a driver was reported to have been present during the interviews, but was not directly observed, the credibility of the response was assessed considering the familiarity of the respondent with the particular area, the level of detail provided and the plausibility of the reason why signs of the driver were no longer visible. This occurred in 12, 12 and 1, plots respectively, in the case of agriculture, charcoal and livestock, of which 9, 12 and 1 interview-only records were accepted. Physical evidence of all categories of driver can be obscured over time by natural regeneration, while crop cultivation can remove evidence of charcoal production, fire and livestock. All fire records are based on observations only.

For the plots on village land (n = 95) and general land (n = 9), most informants (65%) were representatives of the respective village council for the village land, or from the adjacent village for the general land; 17% were either the land owner or occupant; and 18% were other knowledgeable people such as neighbours (5%), other villagers (10%) or, if no-one else was available, the district officer (3%). For the plots on reserved land (n = 16), most informants were either District Officers (38%) or Tanzania Forest Services Agency Officers (38%). Others were Village Council representatives from adjacent villages (19%) or local land owners (5%). 14% of informants were directly involved in the deforestation event.

Use of Open Data Kit for ground survey data collection

Survey data was recorded in an Open Data Kit (ODK) form. Completed forms were periodically uploaded to a cloud server. The plot centre of each point was automatically recorded from the blue-tooth GPS device and saved in the ODK form.

Appendix 1.2 Results

Datasets for the publication are available at:

https://iopscience.iop.org/article/10.1088/1748-9326/ab6b35

Appendix 1.3 References for Appendix 1

Lee, J. S. 1983 Digital image smoothing and the sigma filter. *Computer vision, graphics, and image processing*, **24** (2): 255-269.

Mitchard, E. T., S. S. Saatchi, I. H. Woodhouse, G. Nangendo, N. S. Ribeiro, M. Williams, and P. Meir, 2009 Using satellite radar backscatter to predict above-ground woody biomass: A consistent relationship across four different African landscapes. *Geophysical Research Letters*, **36** (23).

Olofsson, P., G. M. Foody, S. V. Stehman and C. E. Woodcock. 2013 'Making Better Use of Accuracy Data in Land Change Studies: Estimating Accuracy and Area and Quantifying Uncertainty Using Stratified Estimation'. *Remote Sensing of Environment* **129** (February): 122–131. doi:10.1016/j.rse.2012.10.031.

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Appendix 2 Supplementary material for Chapter 4

Supplementary material for the publication ‘Agricultural fallows are the main driver of deforestation in Tanzania.’

The data and codes associated with this paper are openly available from the University of Leeds Data Repository: https://doi.org/10.5518/1295. Results of the structured interviews are available upon reasonable request from the University of Leeds Restricted Access Repository (RADAR).

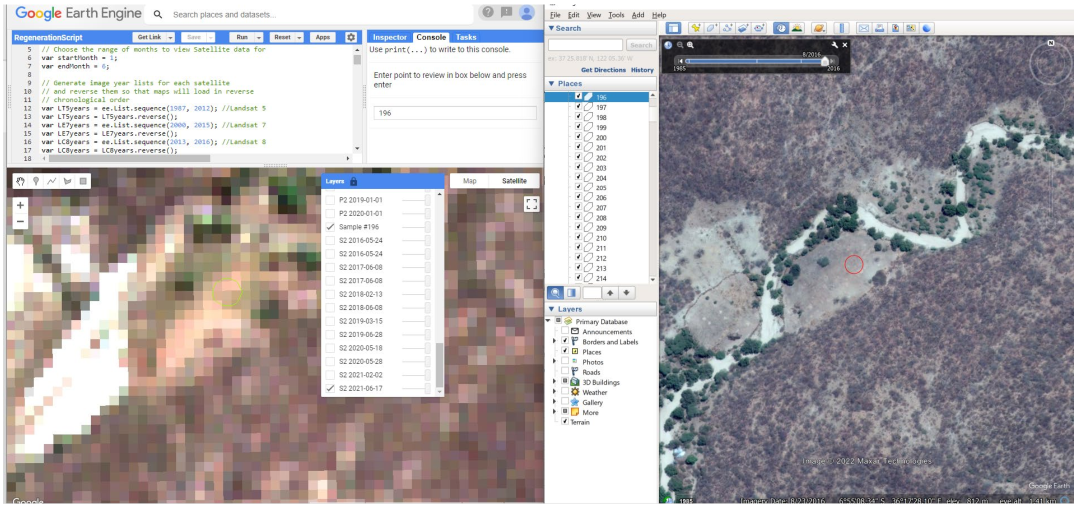
Appendix 2.1 Methods

A.2.1.1 Description of the methods used to label long-term land cover trajectories

To assess land cover change, including rates of regeneration and deforestation, 500 sample points were randomly selected across the study area. Google Earth Engine (GEE) was used to view the random sample points super-imposed on the least cloudy images / data from Landsat 5, 7 and 8, Sentinel 2 and from PALSAR 1 and 2. The images were reviewed visually, and the sample points classified according to the classes described in Table S4. Images are stacked with the oldest images at the top. Using this method, for each point, the land cover change trajectory between 1987 and 2021 was determined.

The Earth Engine script used to display the points and remote sensing data is available at: https://github.com/wmugasha/Regeneration_Study and at https://doi.org/10.5518/1295

High resolution images in Google Earth Pro (GEP) were also used (Supplementary Figure 1). Note the green and red plot boundary on the GEE and GEP screens respectively.



Supplementary Figure 1 Example of Google Earth Engine and Google Earth Pro set-up for land cover change analysis

The land cover change trajectory of the point is then used to classify the point into one of 21 land cover change trajectory classes.

The 21 land cover change classes are:

1. Forest / woodland / bushland remains as forest / woodland / bushland
2. Agriculture remains as agriculture
3. Plantation remains as plantation
4. Agriculture converts to plantation and then converts to agriculture
5. Agriculture converts to forest / woodland / bushland then converts to agriculture then converts to forest / woodland / bushland and then converts to agriculture
6. Agriculture converts to forest / woodland / bushland and then converts to agriculture
7. Forest / woodland / bushland converts to agriculture with no regeneration
8. Forest / woodland converts to agriculture and then to plantation
9. Forest / woodland / bushland converts to other
10. Forest / woodland / bushland converts to agriculture and then converts to forest / woodland / bushland and then converts to agriculture
11. Forest / woodland / bushland converts to agriculture and then converts to forest / woodland / bushland

12. Forest / woodland / bushland converts to agriculture and then converts to forest / woodland / bushland and then to agriculture and then to forest / woodland / bushland
13. Forest / woodland / bushland converts to grassland then converts to forest / woodland / bushland
14. Agriculture converts to forest / woodland / bushland
15. Agriculture converts to other non-forest land cover
16. Agriculture converts to wetland
17. Wetland converts to forest / woodland / bushland then to agriculture
18. Grassland converts to agriculture
19. Grassland remains as grassland
20. Other non-forest land cover remains as other non-forest land cover
21. Wetland converts to agriculture then back to wetland

Plots in classes 11, 12, 13 and 14 are included in the regeneration rate i.e. where the paper states '*Natural regeneration was detected on 5.6% (95% CI: 3.75%–7.99%) or 3.15 Mha of village land in 2021, of which 4.8% (95% CI: 3.1%–7.06%) and 0.8% (95% CI: 0.22%–2.04%) of points were forest and non-forest in 1987, respectively*', the 4.8% figure refers to classes 11, 12 and 13, while the 0.8% figure refers to class 14.

Plots in classes 7, 8, 9 and 10 are included in the deforestation rate.

The time periods for the remote sensing datasets that were viewed as layers in GEE are summarized Supplementary Table 3.

Supplementary Table 3 Time periods of the remote sensing datasets used in the study

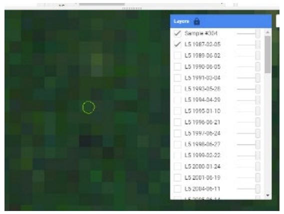
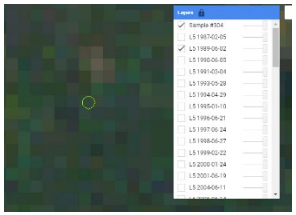
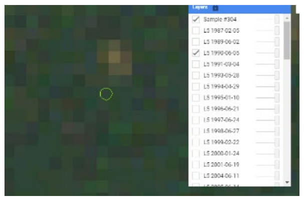
Sensor	1987 - 1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Landsat 5																							
Landsat 7																							
Landsat 8																							
PALSAR 1																							
PALSAR 2																							
Sentinel																							

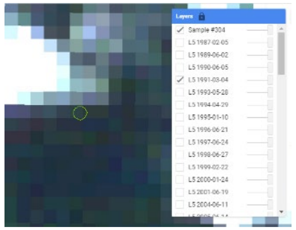
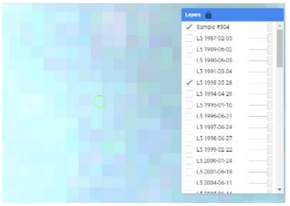
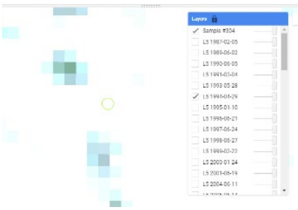
For the Landsat data, Earth Engine selects the most cloud-free image from January to June for each year. For Sentinel 2, the two most cloud free images from January to June for each year, are displayed. January to June coincides with the migration of the inter-tropical convergence zone across Tanzania, bringing high precipitation and greener vegetation cover. The images from this period are easier to interpret than dry season images.

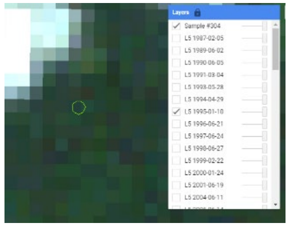
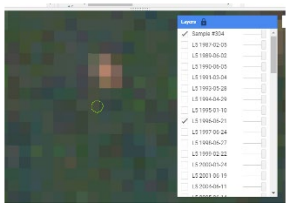
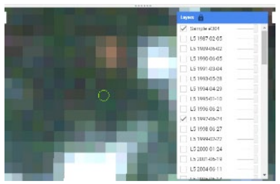
The PALSAR data was taken from the Global PALSAR-2/ PALSAR/JERS-1 Mosaic product, ‘a seamless global synthetic aperture radar (SAR) image created by mosaicking strips of SAR imagery from PALSAR/PALSAR-2’ (Shimada et al 2014). This includes images from different months.

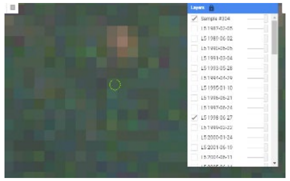
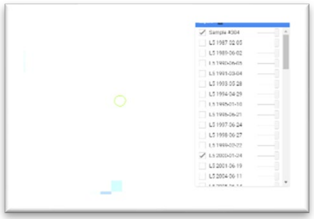
Classification of the land cover requires a careful visual comparison of how the plot changes over time, and how the landscape changes with the seasons. This is important to avoid confusing drier images with deforestation, or wetter images with regeneration. High resolution images provide reliable records of land cover at specific points in time. Where available, these were examined first. They were then compared with Landsat, PALSAR and Sentinel images to understand how that landcover appears in the respective datasets for each point. A worked example is provided below (Supplementary Table 4). In this case, the high-resolution image in 2003 shows that the plot is woodland on the edge of a clearing to the east. This gives an indication of how the woodland to the west, and the cultivation to the east both appear in the contemporaneous Landsat. From this, it can be determined that the plot was woodland in the earlier Landsat 5 images, with degradation in 2001 – 2003, converting to non-forest and cultivation by 2004. The patchwork nature of the land cover, to the east and north-east of the plot, indicates cultivation, rather than livestock grazing. For 2005 – 2016, Landsat 5, 7 and 8 show the land remaining open, confirmed by the high resolution images in 2011, 2013 and 2016. For 2007 – 2009, the low DN values represented in a blue / black colour in the PALSAR layer, confirm a low vegetation cover consistent with cultivation. Higher DN values in 2010, indicate more woody vegetation but the 2011 high resolution image indicates that this is a shrubby crop, rather than regenerating woodland. Similarly in 2017 – 2018, higher PALSAR 2 DN values reflect some bushy cultivation in part of the plot, but the high resolution image indicates that this is cultivation rather than natural regeneration, cleared in the 2019 – 2020 PALSAR 2 and Sentinel 2 data. Based on this analysis, the plot was classified as ‘Forest / woodland / bushland converts to agriculture with no regeneration’. This analysis was repeated for each point.

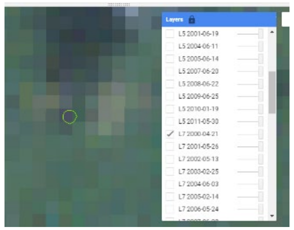
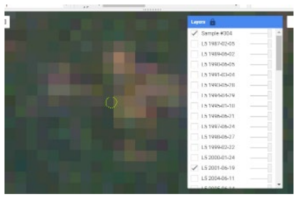
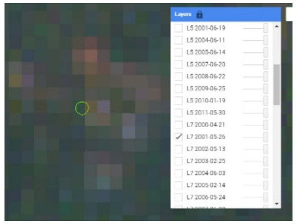
Supplementary Table 4 A worked example of the land cover trajectory classification

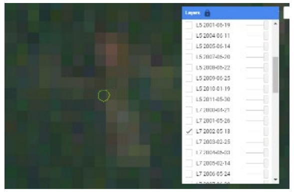
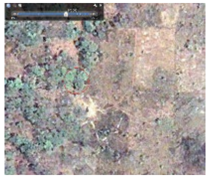
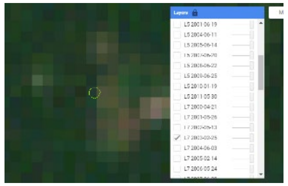
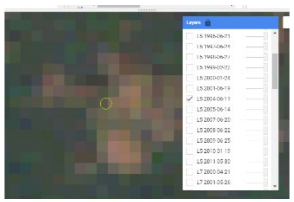
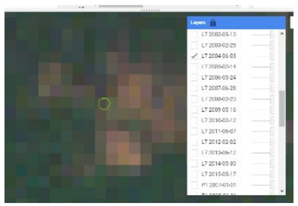
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
1987					W	
1988					No Data	
1989					W	
1990					W	

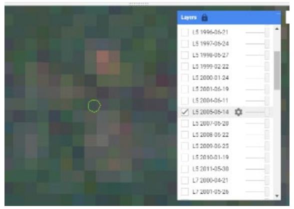
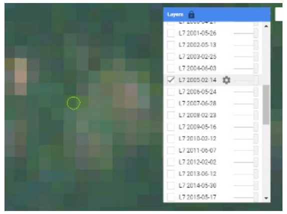
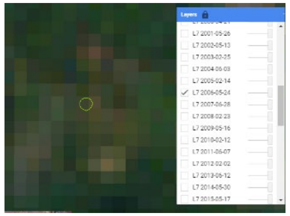
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
1991					**W**	
1992						
1993					**X Cloud cover**	
1994					**X Cloud cover**	

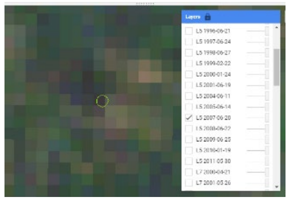
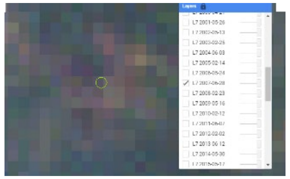
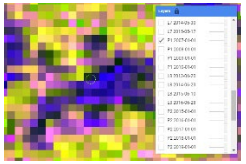
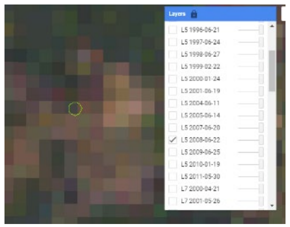
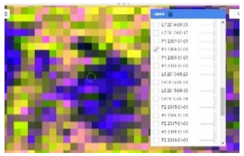
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
1995					**W**	
1996					**W**	
1997					**W**	

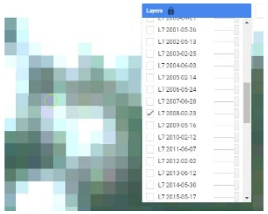
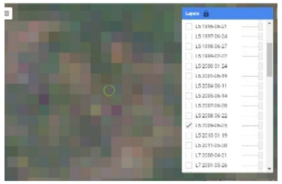
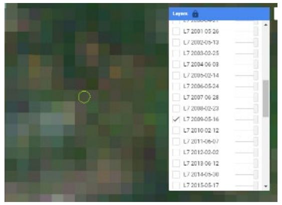
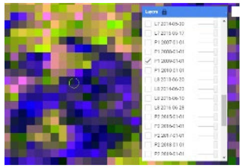
Year	**Google Earth Pro HR Images**	**Landsat**	**PALSAR**	**Sentinel**	**Class**	**Sub-class**
1998					**W**	
1999					**X Cloud cover**	
2000					**X Cloud cover**	

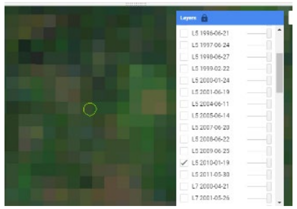
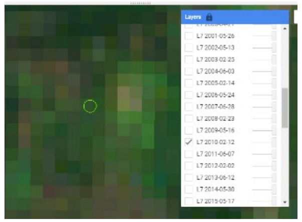
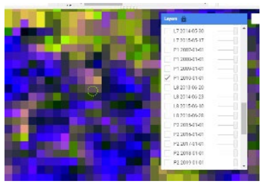
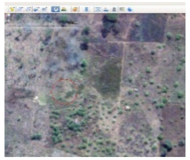
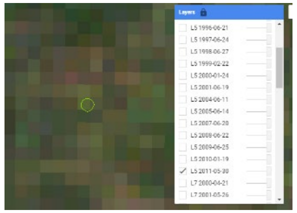
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
						
2001		 			**W**	

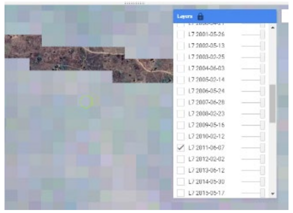
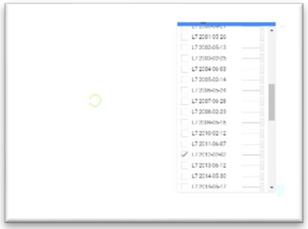
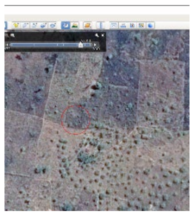
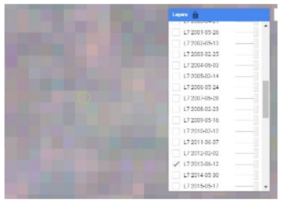
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
2002					**W**	
2003					**W**	
2004		 			**C**	**Cc**

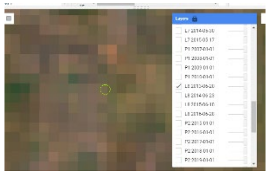
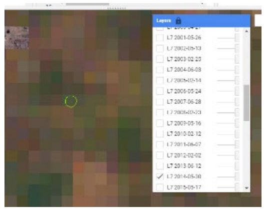
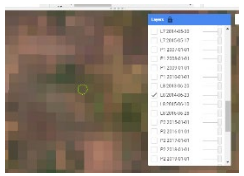
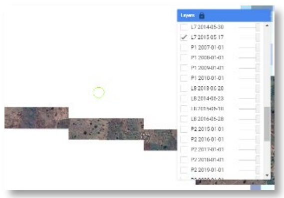
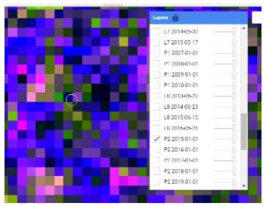
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
2005		 			**C**	**Cc**
2006					**C**	**Cc**

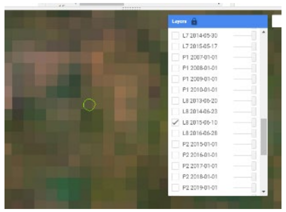
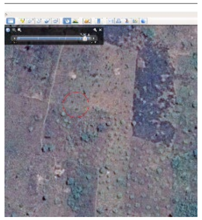
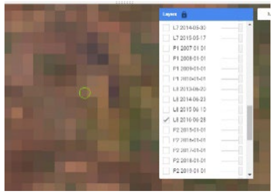
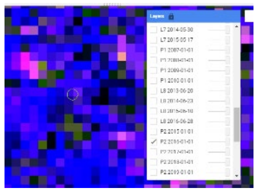
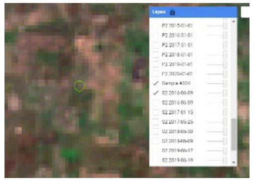
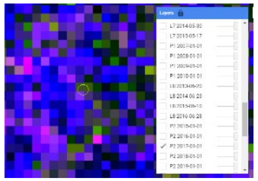
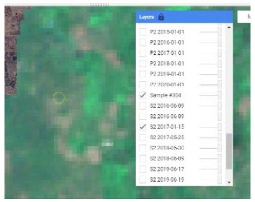
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
2007		 			C	Cc
2008					C	Cc

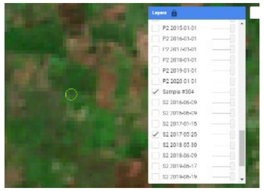
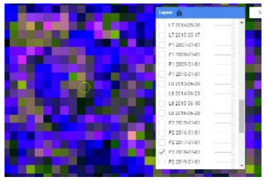
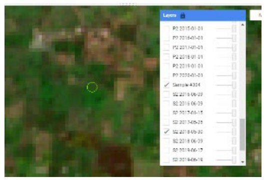
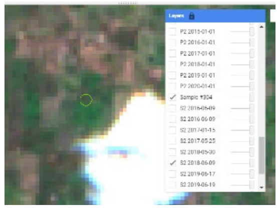
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
						
2009		 			**C**	**Cc**

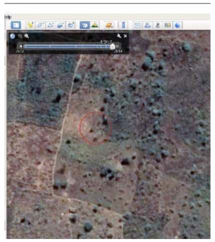
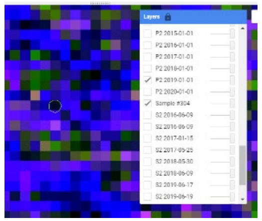
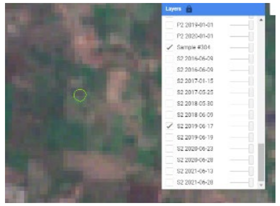
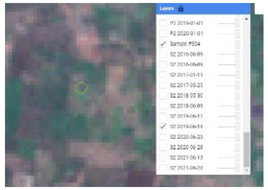
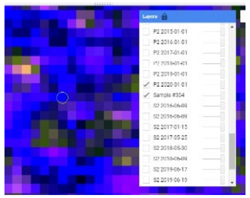
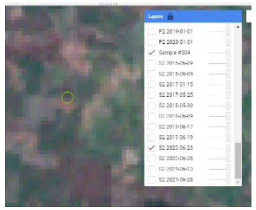
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
2010		 			**C**	**Cc**
2011					**C**	**Cc**

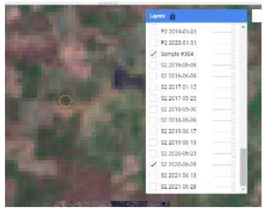
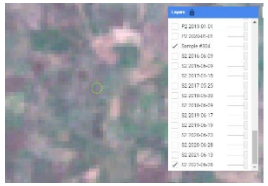
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
						
2012					**No data**	
2013					**C**	**Cc**

Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
						
2014		 			C	Cc
2015					C	Cc

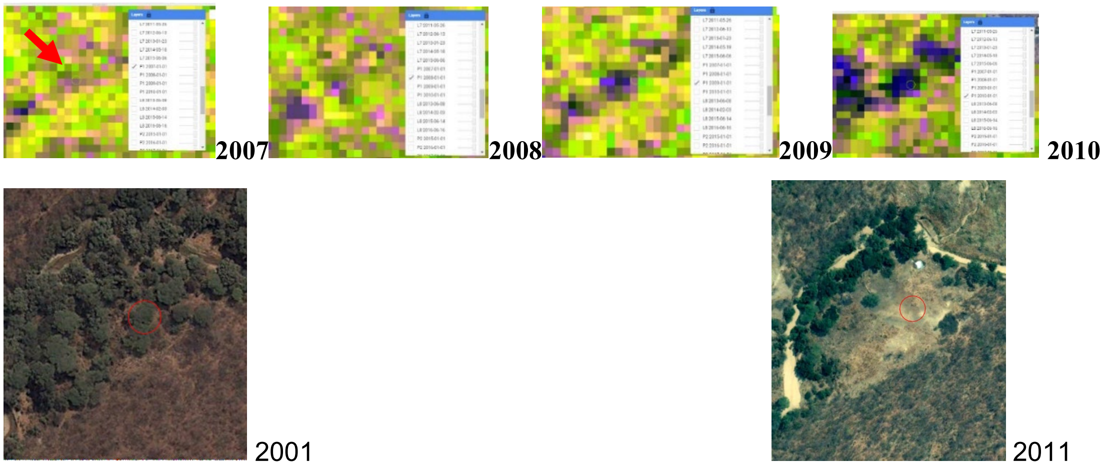
Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
						
2016					**C**	**Cc**
2017					**C**	**Cc**

Year	**Google Earth Pro HR Images**	**Landsat**	**PALSAR**	**Sentinel**	**Class**	**Sub-class**
						
2018				 	**C**	**Cc**

Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
2019				 	**C**	**Cc**
2020					**C**	**Cc**

Year	Google Earth Pro HR Images	Landsat	PALSAR	Sentinel	Class	Sub-class
						
2021				 	**C**	**Cc**

Supplementary Figure 2 Example of deforestation in a PALSAR time-series



For the period 1987 – 1999, there is a reliance on Landsat 5 imagery only. Note that the 30-metre pixel size of Landsat 5 corresponds with the 30 m diameter sample plot. On average (mean and median) there were images for 7 years per point between 1987 – 1999 (min = 1, max = 12). For the ‘forest converts to agriculture with no regeneration’ class, 12 out of the 68 points in that class, were detected as deforestation between 1990 and 1999 solely from Landsat 5 data. After 2000, sample points were classified using data from 2 – 3 sensors, plus VHR images, until 2019 – 2021 when only Sentinel 2 data was used (Supplementary Table 3). With its 10-metre resolution, the Sentinel 2 data provides more detailed information than Landsat on land cover for these final years of the study period.

PALSAR data was reviewed visually and, where appropriate the HV DN value was considered. By comparing, changes in PALSAR over time, land cover changes can be detected. Consider this plot, cleared between 2009 and 2010 (Supplementary Figure 2). The PALSAR data shows clearly the change in land cover from the woody vegetation in 2007 to the cleared non-forest area in 2010. PALSAR data is always used in combination with the other datasets. It has the advantage of being consistently available, including for plots where high cloud cover limits use of Landsat and Sentinel images.

Definitions and reference images were provided for each land cover class. The classification reflects the land cover class in the plot itself (rather than the surrounding land).

Year of deforestation: The most recent year in which a plot transitioned from forest to non-forest was recorded and provided the basis for calculating the median year of deforestation, only for those plots that were forest in 1987 and non-forest in 2021.

Other considerations

Evidence that the plot is not village land

The study area is village land. Care was taken to exclude any plots that were not village land and that had been included erroneously in the sampling. This includes private estates e.g. tea estates or peri-urban areas. Where it was clear that a plot was not village land, it was classified as 'O' with a sub-class of 'Nv' and a comment in the notes column to explain. The study's land cover classes are summarised in Supplementary Table 5, while the land cover definitions and reference images are provided in Supplementary Table 6.

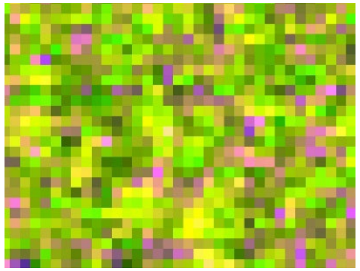
Supplementary Table 5 Summary of land cover classes and codes

Class	**Code**
Forest (not plantation)	F
Plantations and woodlots	Fp
Woodland	W
Bushland (with sub-classes to be noted where confident: Bt = Itigi thicket; Bw = climate bushland; Bsc: Bushland and woodland fallow.	B
Grassland and bamboo	G
Agriculture with sub-classes to be noted where confident: Cc = Herbaceous and grain crops (not trees); Cg = grazed areas / livestock without crops; and Caf = Agroforestry	C
Rocks, ice, sand and other permanently bare areas	R
Water and wetlands	We
Other (with sub-class: NV = not village land)	O
Clouds	X

Class	**Code**
Uncertain	U

Supplementary Table 6 Land cover / land use classes and their definitions

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
Forest (not plantation)	F	A continuous stand of trees many of which may attain a height of 50 m. True high forest has three canopy layers; emergents, middle and lower canopy. The main canopy of semi-mature and mature trees dominates the structure, with a regenerative canopy beneath. Occasional emergents form the uppermost, but fragmented third canopy. Includes lowland, riverine, submontane and montane forests. Also includes mangroves. If mangrove, make a note of this, as this is not expected on village land. Mostly evergreen, with the exception of Coastal Forests which are deciduous.	Typical high res (from E. Usambara)  	*Woodland (closed)* Are there signs of grass between the trees. If yes, classify as woodland. The high res images in Google Earth (30 cm resolution Geo Eye or Quickbird) are particularly useful in determining whether there is grass between trees. Using the dry season images, determine whether it is deciduous. If it is deciduous, classify as	Forest – montane forest, lowland forest, mangrove forest Fhm, Fl, Fm

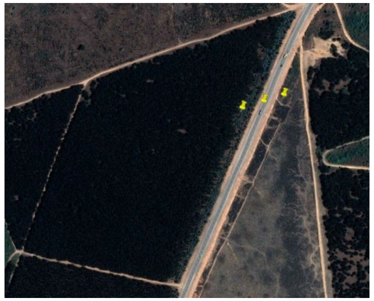
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
		Palsar HV value typically > 2500.	An example of riverine forest  Palsar (from E. Usambara) 	woodland, with the exception of Coastal Forest areas which can be deciduous and should be classified as Forest. Context – what is the surrounding vegetation? If the surrounding vegetation is clearly forest, classify as forest. HV DN value – most pixels should be > 2500 if it is forest.	

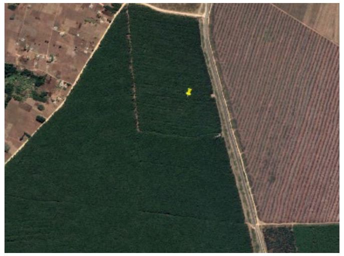
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				Are there emergents? This would signify forest. Consider elevation, with forest more likely to occur at higher elevation due to increased precipitation at higher elevation. *Plantations* Context: look at surrounding vegetation for signs of being a plantation e.g. regular road network, cut lines, distinctive / uniform colour.	

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				Texture: canopy in a forest should be uneven.	
Plantations and woodlots	Fp	Plantations and woodlots of pine, eucalyptus, cypress, teak, casuarina, grevillea, black wattle and acacia used for poles, timber or fuelwood. As the focus of the study is on village land, these may include woodlots of 0.5 hectares. Large commercial plantations would indicate that the land is not village land and should be highlighted in the notes.	Typical plantation and woodlots (Iringa)  	*Forest or woodland* Context – are there clear plantations around it, if so, more likely to be plantation. A regular road network would indicate plantation. Regularly shaped blocks would indicate plantation. Trees planted in lines would indicate plantation. Canopy texture: if the canopy texture is very even, likely to be plantation.	Forest - Plantation Fp

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			Plantation with high mortality giving a more ragged appearance  Plantation in West Usambara	History: check Google Earth imagery to determine whether the area has been cleared. If so, more likely to be plantation. Canopy colour: is the canopy evenly coloured. If so, more likely to be a plantation / woodlot. Compare the colour with a nearby area of forest or woodland. Plantations often appear very dark. Emergents? If there are emergent, likely to be forest.	

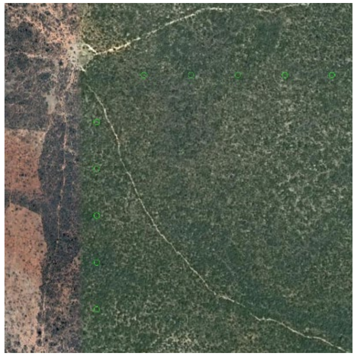
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			 Eucalyptus plantation 	*Agroforestry* Context – Consider the typical land use in the area. For example, if there are many other woodlots in the area, as in Iringa, classify as Fp. If it appears to be fruit trees such as mangoes or coconut trees, classify as C with sub-class Caf.	

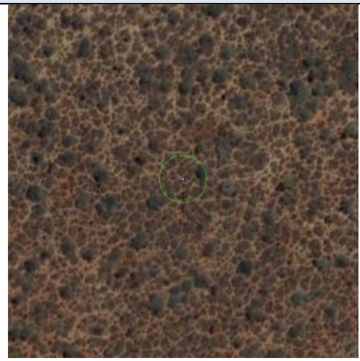
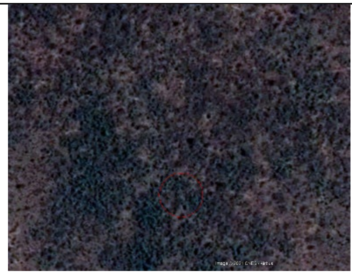
Study class	**Code**	**Definitions (based on NAFORMA, URT 2010)**	**Reference images**	**Distinguishing from look-alike classes**	**Equivalent NAFORMA (sub-) classes**
			Eucalyptus (commercial plantation – not village land)  Eucalyptus (commercial plantation – not village land) 		

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			Black wattle (commercial plantation – not village land) 		
Woodland	W	The canopy coverage in woodland typically ranges between 20–80%, and height between 5–20 m although occasionally being taller. Includes open and closed woodland.	Plot 201	*Forest* See Forest section for distinguishing characteristics.	Woodland – closed woodland Wc, Open woodland Wo

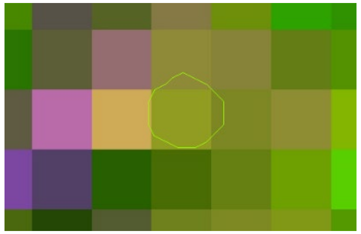
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
		Woodland is characterized by only two main strata - the main canopy itself, which may vary widely in species composition but is generally uniform in stature, and a shrub / herb-layer beneath, which often contains regenerating saplings of the species comprising the main canopy. The understorey is usually dominated by grass. The density of this understorey layer is closely dependent upon the closure of the upper canopy and light penetration to ground level. In areas of Closed Woodland, the ground cover layer may be almost absent. Most woodlands are deciduous.	 	*Bushland* If the canopy width of individual woody objects are > 5 metres, likely to be trees i.e. woodland. There are two ways to determine this: i. examine shadows in Google Earth. Considerable shadow indicates that the trees are several metres tall i.e. more likely to be woodland. ii. crown width – use the ruler tool in Google Earth to measure the crown width of individual stems. There is a roughly linear relationship	

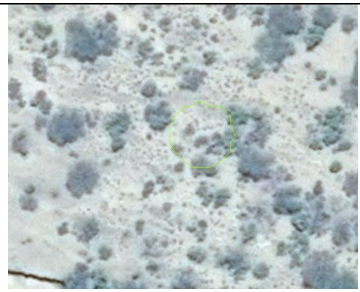
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
		This class includes the Acacia-Commiphora woodland common in northern Tanzania.	  Woodland areas based on NAFORMA results	between crown width and height. So, if crown widths are > 5 metres, it is more likely to be woodland. If >10% of the plot is woodland i.e. covered by objects with > 5 m crown, classify as woodland. Palsar HV DN value – if this is > 2000, likely to be woodland.	

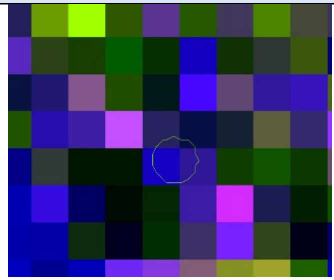
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			 	If the objects have multiple stems, likely to be bushland. If a plot, is really borderline, round up to a higher biomass class i.e. woodland. See Annex 3 for further guidance on bushland / woodland classification for vegetation in north-east Tanzania. *Bushland fallow*	

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				See bushland fallow section. Use the historical imagery slider in Google Earth to check whether it was cleared recently.	
Bushland	B	Canopy height < 5 metres. Bushland is predominantly comprised of plants that are multi-stemmed from a single root base. Bushland occurs in a wide range of densities.		*Woodland* Diameter of objects (bushes / young trees) should be < 5 metres for it to be classified as bushland.	

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				For north-east Tanzania, see Annex 3 for further advice on distinguishing between woodland and bushland. See below for further details and examples and on how to distinguish between sub-classes.	
Sub-classes of Bushland: there are three sub-classes of bushland. These should be indicated in the sub-class column where confident.					

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
Itigi thicket	Bt	A dense thicket in central Tanzania.	  Itigi thicket location	*Bushland* Location – the Itigi thicket is located in central Tz. See map. It appears as a distinctive dark-green in high resolution imagery.	

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
					
Bushland without crops	Bw	Climax bushland. Canopy height < 5 metres. Bushland is predominantly comprised of plants that are multi-stemmed from a single root base. Bushland also occurs in a wide range of densities. Palsar HV DN typically < 1800		*Woodland* ‘Bushland differs from Woodland in two principal ways. Stature is less, rarely exceeding 5 m and normally between 1–3 m in height. Single-stemmed plants are almost non-existent. The exception is when there are occasional trees termed as	Bushland - open bushland Bo, dense bushland Bd

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				emergents.' (NAFORMA Biophysical Manual p. 17) <u>Crown width of objects should be the most important criterion</u> i.e. to classify as woodland, there must clearly be objects with a crown width of 5 m or more covering at least 10% of the plot. Palsar HV DN 1800 Check the width of individual plants. If > 5	

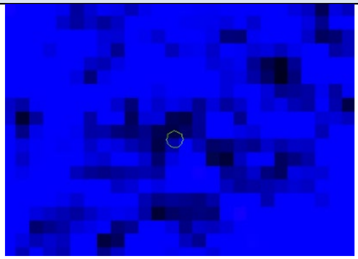
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				metres, likely to be woodland. Context: if the plot is borderline between the woodland and bushland classes, consider the context i.e. if it is surrounded by woodland, classify as Woodland. The Acacia-Commiphora vegetation of northern Tanzania should be classified as woodland. *Grassland*	

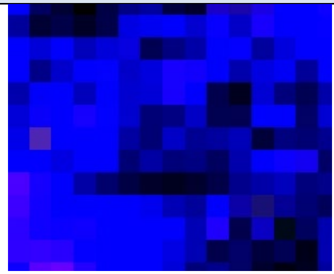
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				See grassland definition.	
Bushland and woodland fallow	Bsc	Areas of natural regeneration, usually following cultivation (but could have been cleared for other purposes e.g. charcoal). No limit on canopy height. Usually in a landscape dominated by agriculture. This is the class of greatest interest to the current study.		*Bushland without crops* Context: if there are no signs of cultivation or roads within 5 km, it should be classified as Bw. If there are signs of cultivation within 5 km, it could be either Bsc or Bw and other factors need to be considered. *Woodland* Recently cleared? Use the historical imagery slider in Google Earth to check whether it was cleared since	Bushland Scattered cropland Bsc;

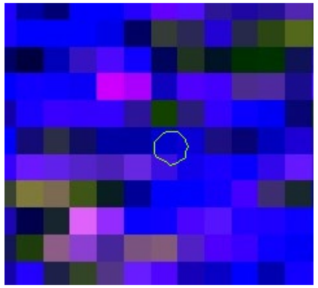
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				1985. If it was cleared and appears to be regenerating, include as Bsc and make a note of when it was cleared in the notes. If >10% of the plot is woodland i.e. covered by objects with > 5 m crown, classify as woodland. Context – is it surrounded by agricultural areas or other fallow areas / abandoned fields? If yes, classify as Bsc. If not, refer to	

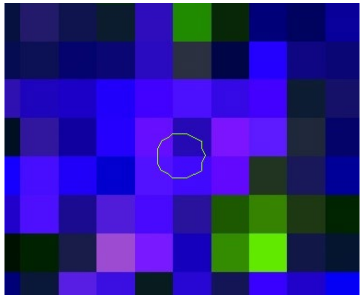
Study class	**Code**	**Definitions (based on NAFORMA, URT 2010)**	**Reference images**	**Distinguishing from look-alike classes**	**Equivalent NAFORMA (sub-) classes**
				distinguishing features for bushland and woodland. *Cultivation* If >10% of the plot is fallow / bushland, classify as Bsc. Fallow / bushland appears with a more textured surface. *Grassland* Context: is it part of a consistent area of tree-less vegetation. If yes, grassland.	

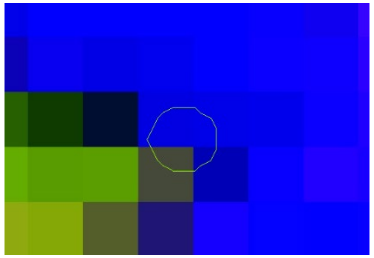
Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				Is there a mosaic of cropland around the plot, if yes, more likely to be Bsc	
Grassland and bamboo	G	Grassland with / without scattered trees or bushes. Open Grassland, is mostly confined, to the plains of the Serengeti, Masai Steppe, and to alpine areas of the Southern Highlands where exposure and edaphic conditions do not allow the natural development of anything more than a grass or herb (NAFORMA). The grassland class includes plots with an assessed ground cover percent of trees or bushes below 10 percent of total.	Example: Plot 260 	*Bushland* Location: Is the plot in the Serengeti, Maasai Steppe or montane areas of the Udzungwas and Southern Highlands? If so, likely to be grassland rather than bushland. % cover of bushes: is <10% of the plot covered in	Grassland – grassland with scattered trees Gw; grassland with scattered bushes Gb; Open grassland GO.

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
		This class also includes areas of bamboo. Where a plot is bamboo, this should be indicated in the notes. This class includes areas of bracken as are common in some montane areas such as the Udzungwa mountains. Palsar HV DN typically < 1800.	 	bushes, if so it should be considered grassland. If a plot, is really borderline, round up to a higher biomass class i.e. bushland or woodland. *Woodland* % cover of trees: is <10% of the plot covered in trees, if so it should be considered grassland. *Cultivation*	

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				Grassy areas in a mix of fields with signs of livestock e.g. enclosures, should be classified as cultivation.	
Agriculture: Crops and grazed areas	C	Includes herbaceous, grain and tree crops (except plantations), and grazed areas.			
There are three sub-classes of crops and grazed areas. These should be indicated in the sub-class column, where confident.					
Crops	Cc	Cultivation with herbaceous crops (e.g. cotton, vegetables, sisal, tobacco, flowers, tea etc) and grain crops (maize, rice etc) where the tree component may be reduced to the occasional fruit tree or	Plot 227	*Burnt areas* Where land is bare due to recent burning, consider the context and allocate to	Cultivated – Herbaceous crops Cbc; Grain crops Cgc; Grassland – Scattered cropland / grassy fallow GSc;

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
		trees retained to demarcate field boundaries. Also includes rice paddies. Grassy areas in a mix of fields with signs of livestock e.g. enclosures, should be classified as cultivation.	  Plot 255	either grassland or cultivated land. Other If one or more buildings occur in a predominantly agricultural plot, classify as 'other'. If a road covers >10% of a predominantly agricultural plot, classify as 'other'.	Woodland – Scattered cropland WSc (if <10% tree cover).

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			  Plot 275		

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			  Tea (not village land)		

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			 Tea (not village land) 		

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
Grazed areas	Cg	Grazed areas that are not bushland or woodland i.e. are predominantly covered in grass and herbs. Livestock trails and livestock enclosures are often visible.		*Grassland* If the land is in a matrix of fields, with grazed areas, classify as Cg. The grassland class is only for natural grassland such as the plains of the Serengeti, Masai Steppe, and montane grassland. Consider the altitude, if low altitude grazed grassland, likely to be Cg.	

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
Agroforestry	Caf	The agroforestry systems contain permanent tree crops (timber and fruit) which are mixed with permanent and annual agricultural crops. The tree crops which form the upper canopy act as shade to the lower canopy crops. This class includes land with >10% tree crops. Common trees crops in this class include mango, cashewnut and coconut palm trees. Others include avocado.	  Agroforestry	*Plantations* Check for rings of open land around the trees. If these are visible, likely to be agroforestry, whereas plantation trees tend to be planted more closely. *Bushland fallow* Measure how much of the plot is covered by tree. If > 10% = agroforestry. Consider stems that are inside the plot.	Cultivated – Agroforestry Caf; Wooded crops Cwc Woodland – Scattered cropland WSc (if >10% tree cover).

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
			 Avocado 	*Cultivation* Where there are trees mixed with crops, consider the location of the stems. If stems are outside of the plot, more likely to be cultivation. If stems are in the plot and > 10% tree cover, classify as agroforestry.	

Study class	**Code**	**Definitions (based on NAFORMA, URT 2010)**	**Reference images**	**Distinguishing from look-alike classes**	**Equivalent NAFORMA (sub-) classes**
Rocks, ice, sand and other permanently bare areas	R	<u>Permanently</u> bare areas such as rock outcrops, ice, sandy beaches and soda ash. Vegetation is absent. Does not include cleared fields as these are only temporarily bare.	Rock outcrop in East Usambaras 	*Cultivated areas and Bushland fallow* Most commonly confused with cleared fields. As these are temporarily cleared, these should be allocated to C. *Burnt areas* Where land is bare due to recent burning, consider the context and allocate to either grassland or cultivated land.	Open land – Bare soil Bsl; Cosatal bare land Sc; Rock outcrops Ro; Ice-cap / snow Ice

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				Grassland Context – consider whether the area is more likely to be dry grassland. Again this would not count as 'permanently' base and as such should be classified as G rather than R. *Wetlands* Where an area is bare but is periodically inundated such as lake margins, this should be classed as Water (wetland). Using the Google Earth time series can help to	

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
				identify areas that are periodically inundated.	
Water	We	Ocean, inland water (lakes, rivers) and wetlands. Wetlands are water logged seasonally inundated areas where cultivation is absent. A point should be classified as wetland where >10% of the sample point is wetland. Excludes rice paddies or equivalent.		*Cultivated* Rice paddies or equivalent should be classed as C. *Permanently bare areas* Where land is periodically inundated, it should be classified as water, unless it is cultivated (see above).	Water - Ocean Wo; Inland water Wi; Wetlands Wet

Study class	Code	Definitions (based on NAFORMA, URT 2010)	Reference images	Distinguishing from look-alike classes	Equivalent NAFORMA (sub-) classes
Other	O	Urban and rural built-up areas, air fields, and infrastructure. This includes roads, houses and yards. Where roads cover > 10% of the sample point, it should be classified as Other. Where one or more buildings occur in the plot, classify as 'other'. This is to avoid selecting points for the survey where it will be difficult to find sufficient land for a sample point.	 	*Cultivation* Where a road covers > 10% of a plot dominated by cultivation, classify as 'other'. If there are one or more houses in a cultivated area, classify as 'Other'.	Other O Urban and rural built-up areas, air fields and infrastructure.

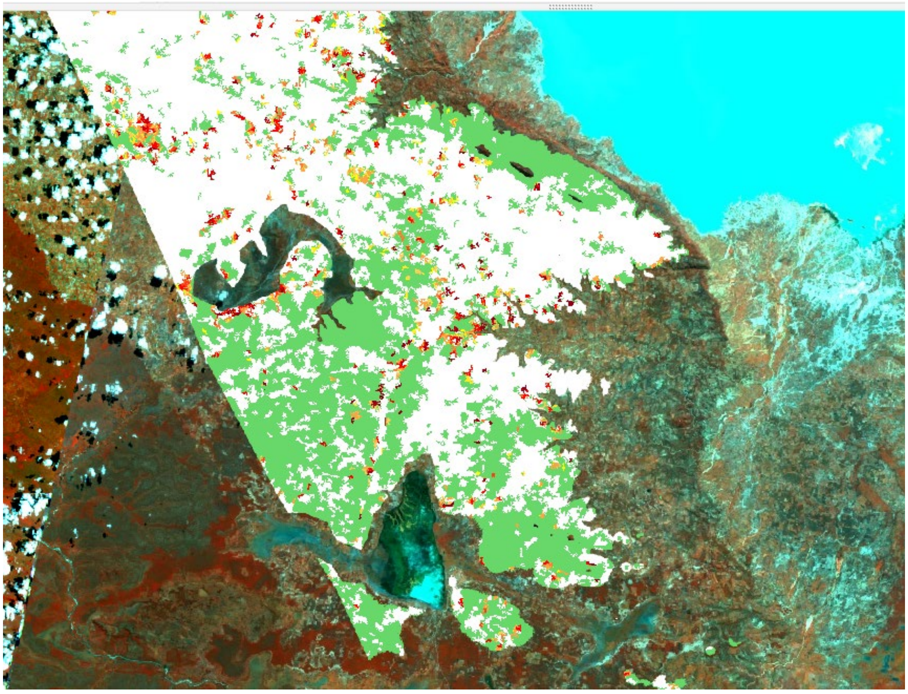
Study class	**Code**	**Definitions (based on NAFORMA, URT 2010)**	**Reference images**	**Distinguishing from look-alike classes**	**Equivalent NAFORMA (sub-) classes**
		Where it is clear that the land is not village land e.g. in a large municipal area or large plantation, peri-urban area or industrial area, this should be listed as 'NV' in the sub-class column.			
Clouds	X	Plot is obscured by clouds in all recent images.			None
Uncertain	U	It is not possible to classify the plot. A brief explanation of the issue should be provided in the notes.			

A.2.1.2 Description of the clustered sampling strategy for the field survey sample plots

For the field survey work, ten clusters were identified with between 17 and 20 field survey sample plots (FSSPs) per cluster. The ten sample clusters were identified from the 500 remote-sensing sample points, randomly distributed across village land. Each of these 500 points were analysed for signs of regeneration (see A 2.1.1). Regeneration was detected in 28 sample points. From these 28 sample points, the first 10 sample points with regeneration were used to select the ten cluster locations. Where two points occurred in the same district, the next sample point with regeneration was used (occurred once). This approach ensured that the cluster locations were based on random sampling and so could be considered representative of the broader study area, i.e. village land. The original randomly selected sample point with regeneration (i.e. from the 500-sample set) was used as one FSSP. An additional 19 FSSPs were then identified visually as areas of regeneration close to the original, randomly selected sample point. The FSSPs were intended to be comparable to the original point and so the search area was constrained by altitude with a maximum range of +/- 150 m above sea level (a.s.l.). The FSSPs were identified visually using the same combination of Google Earth Engine datasets and high-resolution Google Earth images as is described in Section 2.1. To detect areas of regeneration around the original point, an Earth Engine script was used (A 2.1.3) using PALSAR to detect areas of vegetation increase. Although this was not reliable as a definitive indication of regeneration, it was useful in detecting areas of vegetation gain.

Supplementary Figure 3 An example of mapped regeneration in Manyoni District

Using PALSAR data, areas of regeneration are detected and displayed in yellow, orange and red, depending regeneration time, with yellow as the longest and red as the shortest regeneration times.



Criteria for inclusion were a transition from non-forest to forest between 1987 and 2021 comprising an area of regeneration of at least 15 m radius and appearing as forest in 2021. Where possible, within each cluster, plots were selected to provide a range of different regeneration ages. Once a point of regeneration had been identified, its land cover change history was documented using the same approach as is described in A2.1.1 with the land cover being classified for every year for which one or more image was available. This process enabled the regeneration time to be estimated.

A.2.1.3 Earth Engine script for review of 1987 – 2021 data

A Google Earth Engine Script is used to view the random sample points using the least cloudy images / data from Landsat 5, 7 and 8, Sentinel 2 and PALSAR 1 and 2. Images are loaded with the oldest images at the top. The images were reviewed visually and the sample points classified according to the classes described in Supplementary Table 6. The script is available at: https://doi.org/10.5518/1295

A.2.1.4 Plot information form

The form used to collect general data on the Field Survey Sampling Plots.

Plot ID		
start date and time		
end date and time		
Upload Panoramic Photo of Plot from Center		
Plot Center Point (Make sure Bluetooth GPS connected)	_Plot Center Point (Make sure Bluetooth GPS connected)_latitude	
	_Plot Center Point (Make sure Bluetooth GPS connected)_longitude	
	_Plot Center Point (Make sure Bluetooth GPS connected)_altitude	
	_Plot Center Point (Make sure Bluetooth GPS connected)_precision	
Name (First and Last) of Enumerator (person filling in data)		
Phone Number of Enumerator		
Who else was involved in surveying this point?	Who else was involved in surveying this point?/Member of Village Council	
	Who else was involved in surveying this point?/Member of VNRC or VLUM	
	Who else was involved in surveying this point?/Other Village Rep Appointed by VC	
	Who else was involved in surveying this point?/District Officer	
	Who else was involved in surveying this point?/TFS Officer	
	Who else was involved in surveying this point?/TANAPA Officer	
	Who else was involved in surveying this point?/Private Land Owner or Representative	
	Who else was involved in surveying this point?/other	
Current Land Use / Land Cover		
Percent Tree Canopy Cover Over 3 meters	<10%	
	10-40%	
	>40%	
Tallest Tree Height (meters)		
Average Tree Height (meters)		

A.2.1.5 Plot observations form

Form used to collect data on observed land use in the FSSPs.

Plot Number:

Enumerator:

Date:

Season / comments about seasonality -

Record all signs of disturbance using the following categories.

Livestock

Select all signs of livestock within the 15 m radius plot. More than one response can be selected.

Animals seen within the vicinity of the plot (including animals within ~ 50 metres of the plot)

☐ Cattle
☐ Goats
☐ Sheep
☐ Other. Specify___________________________

Dung

☐ Cattle
☐ Goats
☐ Sheep
☐ Unknown
☐ Other. Specify___________________________

Signs of grazing or browsing

☐ Cattle
☐ Goats
☐ Sheep
☐ Unknown
☐ Other. Specify ___________________________
☐ No signs of livestock

Comments on livestock e.g. comments on abundance / grazing pressure and its impact on regeneration.

Signs of wildlife including elephants within the 15-m radius plot

Select all signs of livestock within the 15 m radius plot. More than one response can be selected.

Animals seen within the vicinity of the plot (including animals within ~ 50 metres of the plot)

☐ Antelope and gazelles
☐ Elephants
☐ Buffalo
☐ Other. Specify________________________

Dung

☐ Antelope and gazelles
☐ Elephants
☐ Buffalo
☐ Other. Specify________________________

Signs of grazing or browsing

☐ Antelope and gazelles
☐ Elephants
☐ Buffalo
☐ Other. Specify________________________

Signs of elephant damage

☐ Bark removal from trees
☐ Felling trees
☐ Other. Specify________________________

☐ No signs of wildlife

Comments on wildlife e.g. comments on abundance / grazing pressure and its impact on regeneration.

Crop cultivation within the 15 m radius vegetation plot

Are there signs of crop cultivation within the vegetation plot?

☐ Yes

☐ No

If yes, proceed to the following questions:

Crop types observed

☐ Maize

☐ Beans

☐ Cashew

☐ Cassava

☐ Citrus (lime / orange / lemon)

☐ Coconut

☐ Cowpea

☐ Mango

☐ Peppers

☐ Potato

☐ Rice

☐ Sesame

☐ Sorghum

☐ Sunflower

☐ Squash / pumpkin

☐ Sweet potato

☐ Tobacco

☐ Tomato

☐ Unknown

☐ Other. Specify__________________________

Crop stages visible

☐ Vegetation clearing for crop cultivation

☐ Tillage for crop cultivation

☐ Growing crops

☐ Crop residues

☐ Other. Specify________________________

Cultivated area (area of land cultivated as distinct from natural vegetation)

☐ < 0.5 hectares (25 m x 25 m)

☐ 0.5 – 5 hectares

☐ >5 hectares

Comment________________________

Remnant trees in a cultivated area

Are there any remnant mature trees left in fields within 50 m of the vegetation plot?

☐ Yes

☐ No

☐ Don't know.

☐ Comment_________________

Signs of tillage practice within 50m of the vegetation plot

☐ >5 stumps remain within the cultivated area

☐ 1-5 stumps remain within the cultivated area

☐ 0 stumps remain within the cultivated area

☐ Signs of mechanized cultivation (using a tractor or equivalent)

☐ Other / Comment

Distance from vegetation plot edge to nearest patch of natural vegetation (at least 0.5 ha)

☐ 0 - 10 m

☐ 10 m – 50 m

☐ >50 m

☐ No natural vegetation visible

☐ Other / Comment. Specify_________________________

Fire within the 15 m radius plot

Are there signs of burning within 50m of the edge of the plot?

☐ Yes

☐ No

☐ Unknown

Are there signs of burning within the plot?

☐ Yes

☐ No

If yes, proceed to next question:

If yes, what proportion of the plot has been burnt?

☐ 1% - 25%

☐ 25% - 50%

☐ ≥ 50 %

Comments on fire______________________

Signs of charcoal production within the 15 m radius vegetation plot

Are there signs of charcoal production activities within the plot?

☐ Yes

☐ No

If yes, proceed to next question:

Signs of charcoal production observed

☐ Charcoal bags

☐ Charcoal kiln

☐ Charcoal kiln scar

☐ Wood cutting for charcoal making

☐ Other. Specify________________________

Comments on observations of charcoal e.g. indications of when production occured__________________________

Signs of tree cutting within the 15 m radius vegetation plot

Are there signs of tree cutting within the 15 m plot?

☐ Yes

☐ No

Settlement and infrastructure within the 15 m radius vegetation plot

Are there settlements, roads or infrastructure within the vegetatino plot?

☐ Yes

☐ No

If yes, proceed to next question:

Types of settlement, road, infrastructure observed

☐ Unpaved road (e.g. mud track)

☐ Paved road

☐ Temporary dwelling

☐ Permanent house – poles and mud walls

☐ Permanent house – mud brick walls

☐ Permanent house – cement brick walls

☐ Other structure / infrastruction. Specify___________________________

A.2.1.6 Structured interview questions

Research title: Woodland regeneration on village land in Tanzania

Information Note for Participants (read in Swahili to all those participating in the interviews)

Hello my name is________________. I work for xxx as a____________________.

The title of the research is 'Woodland regeneration on village land in Tanzania'.

You are being invited to take part in this research. Before you decide it is important for you to understand why the research is being done and what it will involve. I am going to explain about the research. Please ask us if there is anything that is not clear or if you would like more information.

The purpose of the research is to find out about how woodlands grow under different conditions. This area is one of 180 points across the country where we will be carrying out the research.

We would like to include you and this area in our study. If you agree to participate, we will note down some observations of this area, measure the vegetation and take a photograph. We will ask you some questions about the history of this land and how it has been used for agriculture and to provide forest products like charcoal and timber. Wild animals can also affect how trees grow so we are also interested in how animals such as antelopes, elephants and even insects may have affected the area. Fire can also affect how trees grow so we will also ask you about burning in the area.

A representative of the village council has identified you as someone knowledgeable about this area.

The information will be used to write a report and a scientific paper. A summary of the research will also be shared with the government. Your identity will be kept secure and will not be exposed in the reporting and dissemination of results. The data and results may be used by other researchers. The data will not be traceable to you.

The interview takes approximately 30 minutes. I need you to answer the questions as accurately as you can. If you don't know the answer to a question or you don’t feel comfortable answering it, that’s fine, just let me know and I will move on to the next question.

In most of the questions I am going to ask about how the land in our survey plot. This is the survey plot. (*Enumerator indicates location of the plot*.)

Your participation in this study is voluntary and you have the right to choose either to participate or not. If you wish to participate, you have the right to choose not to answer any particular question and you can choose to stop the interview at any time. If you do decide to take part you will be given this information sheet to keep. Do you have any questions?

Name of interviewer:___________________

Date:________________________________

Sample point code:____________________

Village name:________________________

District:_____________________________

Are you willing to participate? [Please circle the relevant response]

☐ Yes

☐ No (If "No", note it down and then end the interview).

What is your main profession?

☐ Farmer

☐ Other. Specify_______________

Do you hold a position in the village e.g. village council member, VEO etc?

☐ Yes

☐ No

Looking at the vegetation plot i.e. answers should refer to part or all of the vegetation plot:

Which village does this land belong to?

Name of village:_______________

Is the land within 100 metres of the village boundary?

☐ Yes

☐ No

☐ Other. Specify_______________

Is the land part of a village land forest reserve?

☐ Yes

☐ No

☐ Don’t know

☐ Other. Specify______________

If yes, when was the village land forest reserve established?

Year:

Is the village land forest reserve still protected by the community?

☐ Yes

☐ No

☐ Don’t know

☐ Other. Specify______________

Can you tell me the history of setting up the village land forest reserve?

☐ Yes

☐ No

☐ Don’t know

☐ Other. Specify______________

If yes, when was the wildlife management area established?

Year:____________

Is the wildlife management area still protected by the community?

☐ Yes

☐ No

☐ Don’t know

☐ Other. Specify______________

If, the land is not a VLFR or WMA, proceed with further questions

Do you own this land?

□ Yes

□ No

□ Other. Specify_______________

If yes, for how long have you owned the land?

Years:__________________

If no, how familiar are you with the history of the land?

□ Very

□ Moderately

□ Not very familiar

□ Other. Specify_______________

Has the farm been cultivated at any time in the last 35 years?

□ Yes

□ No

□ Other. Specify_______________

Have you farmed this land at any time in the last 35 years?

□ Yes

□ No

□ Other. Specify_______________

Are you currently farming on this plot?

□ Yes

□ No

□ Other. Specify_______________

If yes, to any of the previous questions about agriculture, please proceed:

I am now going to ask some questions about the history of farming in the vegetation plot.

When was the last time that crops were cultivated here?

□ Indicate year: ______________

□ Don’t know

When was woodland last cleared to prepare for cultivation?

□ Indicate year: ______________

□ Don’t know

Was that the first time that woodland was cleared in this area, as far as you know?

□ Yes

□ No

□ Other. Specify______________

If no, how many times has woodland been cleared previously in this area.

□ Number of times cleared___________

Ask relevant exploratory questions and document_______________

What is the main crop that has been cultivated here over the last five years?

□ Maize
□ Beans
□ Cashew
□ Cassava
□ Citrus (lime / orange / lemon)
□ Coconut
□ Cowpea
□ Mango
□ Peppers
□ Potato
□ Rice
□ Sesame

☐ Sorghum

☐ Sunflower

☐ Squash / pumpkin

☐ Sweet potato

☐ Tobacco

☐ Tomato

☐ Unknown

☐ Other. Specify___________________________

What other crops have been cultivated here over the last five years?

☐ Maize

☐ Beans

☐ Cashew

☐ Cassava

☐ Citrus (lime / orange / lemon)

☐ Coconut

☐ Cowpea

☐ Mango

☐ Peppers

☐ Potato

☐ Rice

☐ Sesame

☐ Sorghum

☐ Sunflower

☐ Squash / pumpkin

☐ Sweet potato

☐ Tobacco

☐ Tomato

☐ Unknown

☐ Other. Specify___________________________

What kind of tools have been used to clear the plot?

☐ Hoe

☐ Panga

☐ Tractor

☐ Oxen-pulled plough

☐ Unknown

☐ Other. Specify_________________________

I am now going to ask you about burning in the survey plot.

When was the last time that the plot was burned?

Indicate year ____________________________

How regularly has the plot been burned?

☐ More than once per year

☐ Annually

☐ Regularly but less than once per year

☐ Only at time of initial clearing from woodland

☐ Other response. Specify_______________________

If response indicates regular burning, ask:

At what time of year is the plot usually burned?

Specify____________________________

I am now going to ask you about charcoal production in the survey plot.

Has this area been used for charcoal production?

☐ Yes

☐ No

☐ I don't know.

☐ Other ___________________________

If yes:

When was the last time that this area was used for charcoal production?

☐ Indicate year: ______________

☐ Don't know

Were any trees cut down in the plot for charcoal?

☐ Yes

☐ No

☐ I don't know.

Were there any charcoal kilns inside the plot?

☐ Yes

☐ No

□ I don’t know.

I am now going to ask you about tree felling for poles and timber in the survey plot.

Has this area been used to provide poles or timber?

□ Yes

□ No

□ I don’t know.

□ Other ___________________________

If yes:

When was the last time that poles or timber were harvested from the survey plot?

□ Indicate year: ______________

□ Don’t know

I am now going to ask you about livestock grazing in the survey plot.

Have livestock been grazed in the survey plot over the last 30 years?

□ Yes

□ No

□ I don’t know.

□ Other ___________________________

If yes:

When was the last time that livestock were grazed in the survey plot?

□ Indicate month and year: ________________

□ Don’t know

For how many months of the year are livestock grazed here usually

□ <1 month

□ 1 – 6 months

□ 6 – 12 months

What kind of livestock have been grazed here? (more than one response possible)

□ Cattle

□ Goats

□ Sheep

□ Unknown

□ Other. Specify ________________________

From where do the people grazing livestock in this area come from?

□ Village residents

□ Non-resident of the village

□ Other / Comment. Specify _________________________

How many livestock have been grazed here over the last year?

□ <10

□ 10 – 50

□ >50

I am now going to ask you about wildlife in the survey plot.

Do any of the following animals graze in this area?

□ Antelopes and gazelles (duiker, bushbuck, impala)

□ Elephants

□ Buffalo

If yes, to elephants

When was the last time that you were aware of elephants pass through this area?

Year_______________________

Have elephants pulled down any trees in this area?

□ Yes

□ No

□ I don’t know.

□ Other _________________________

Have there been any outbreaks of invertebrate populations in this area such as locusts or fall-army worm?

□ Yes

□ No

□ I don’t know.

□ Other _________________________

If yes, when was the last time that the area was affected?

Year______________________

What kind of outbreak was it?

- ☐ Locust
- ☐ Fall army worm
- ☐ Other

Can you tell me anything else about the history of the land that might have affected the vegetation in the survey plot?

Document response: ________________

Thank you for participating in the survey. Here is a copy of the information about the survey.

Are you happy for us to use the information that you have provided in the survey?

- ☐ Yes
- ☐ No

A.2.1.7 R script to calculate biomass and species richness

Note that the datasets referred to in the script are available at https://doi.org/10.5518/1295.

A.2.1.8 Random forest script in R

```
#These rows give access to packages needed to run this script

library(readr)

library(tidyverse)

library(ggplot2)


#locate the dataset on my c drive in the folder RData and call it 'rfdataset'.

rfdataset <- read_csv("C:\\RData\\all_regen.csv")

#attach the data.

attach(rfdataset)

#convert the character data columns into factors

rfdataset$charcoal<-as.factor(rfdataset$charcoal)

rfdataset$cultivation<-as.factor(rfdataset$cultivation)

rfdataset$livestock<-as.factor(rfdataset$livestock)

rfdataset$fire<-as.factor(rfdataset$fire)

rfdataset$deforestation_driver<-as.factor(rfdataset$deforestation_driver)

rfdataset$conservation<-as.factor(rfdataset$conservation)

rfdataset$tree_cutting<-as.factor(rfdataset$tree_cutting)

rfdataset$goats<-as.factor(rfdataset$goats)

rfdataset$elephant<-as.factor(rfdataset$elephant)

names(rfdataset)

str(rfdataset)

view(rfdataset)

#now we build our random forest. In this case for all plots.

#We set ntree to 601. By setting it to an odd number, it includes a 'tie breaker' element.
```

```
#BIOMASS excluding remnant trees but including stumps

modelrf <- randomForest(norem_agb ~ vegetation + time + livestock + charcoal
                + conservation + cultivation + district
                + fire + deforestation_driver + precipitation + tree_cutting,
                data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                type = regression)

modelrf

print(modelrf)

varImpPlot(modelrf)

importance(modelrf)

varUsed(modelrf)

plot(modelrf)

#Just for Miombo Woodland Plots excluding remnants but including stumps

modelrfmw <- randomForest(norem_agb[vegetation=="MW"] ~ + time[vegetation=="MW"]
                + livestock[vegetation=="MW"] + charcoal[vegetation=="MW"]
                + conservation[vegetation=="MW"] + district[vegetation=="MW"]
                + cultivation[vegetation=="MW"]
                + fire[vegetation=="MW"] + deforestation_driver[vegetation=="MW"]
                + precipitation[vegetation=="MW"] + tree_cutting[vegetation=="MW"],
                data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                type = regression)

modelrfmw

print(modelrfmw)

varImpPlot(modelrfmw)

importance(modelrfmw)

varUsed(modelrfmw)

#Just for Bushland Plots excluding remnants but including stumps

modelrfba <- randomForest(norem_agb[vegetation=="BA"] ~ time[vegetation=="BA"]
                 + livestock[vegetation=="BA"] + charcoal[vegetation=="BA"]
                 + conservation[vegetation=="BA"] + district[vegetation=="BA"]
```

```
                 + cultivation[vegetation=="BA"]
                 + fire[vegetation=="BA"] + deforestation_driver[vegetation=="BA"]
                 + precipitation[vegetation=="BA"] + tree_cutting[vegetation=="BA"],
                 data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                 type = regression)
modelrfba
print(modelrfba)
varImpPlot(modelrfba)
importance(modelrfba)
varUsed(modelrfba)
#Just for lowland forest Plots excluding remnants but including stumps
modelrfcl <- randomForest(norem_agb[vegetation=="CL"] ~ time[vegetation=="CL"]
                 + livestock[vegetation=="CL"] + charcoal[vegetation=="CL"]
                 + conservation[vegetation=="CL"] + district[vegetation=="CL"]
                 + cultivation[vegetation=="CL"]
                 + fire[vegetation=="CL"] + deforestation_driver[vegetation=="CL"]
                 + precipitation[vegetation=="CL"] + tree_cutting[vegetation=="CL"],
                 data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                 type = regression)
modelrfcl
print(modelrfcl)
varImpPlot(modelrfcl)
importance(modelrfcl)
varUsed(modelrfcl)
#SPECIES RICHNESS
modelrfspr <- randomForest(spr ~ vegetation + time + livestock + charcoal
                + conservation + cultivation + district
                + fire + deforestation_driver + precipitation + tree_cutting,
                data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                type = regression)
```

```
modelrfspr
print(modelrfspr)
varImpPlot(modelrfspr)
importance(modelrfspr)
varUsed(modelrfspr)
plot(modelrfspr)
#Just for Miombo Woodland Plots
modelrfsprmw <- randomForest(spr[vegetation=="MW"] ~ + time[vegetation=="MW"]
                 + livestock[vegetation=="MW"] + charcoal[vegetation=="MW"]
                 + conservation[vegetation=="MW"] + district[vegetation=="MW"]
                 + cultivation[vegetation=="MW"]
                 + fire[vegetation=="MW"] + deforestation_driver[vegetation=="MW"]
                 + precipitation[vegetation=="MW"] + tree_cutting[vegetation=="MW"],
                 data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                 type = regression)
modelrfsprmw
print(modelrfsprmw)
varImpPlot(modelrfsprmw)
importance(modelrfsprmw)
varUsed(modelrfsprmw)
#Just for Bushland Plots
modelrfsprba <- randomForest(spr[vegetation=="BA"] ~ time[vegetation=="BA"]
                 + livestock[vegetation=="BA"] + charcoal[vegetation=="BA"]
                 + conservation[vegetation=="BA"] + district[vegetation=="BA"]
                 + cultivation[vegetation=="BA"]
                 + fire[vegetation=="BA"] + deforestation_driver[vegetation=="BA"]
                 + precipitation[vegetation=="BA"] + tree_cutting[vegetation=="BA"],
                 data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                 type = regression)
modelrfsprba
```

```
print(modelrfsprba)

varImpPlot(modelrfsprba)

importance(modelrfsprba)

varUsed(modelrfsprba)

#Just for lowland forest Plots

modelrfsprcl <- randomForest(spr[vegetation=="CL"] ~ time[vegetation=="CL"]
                  + livestock[vegetation=="CL"] + charcoal[vegetation=="CL"]
                  + conservation[vegetation=="CL"] + district[vegetation=="CL"]
                  + cultivation[vegetation=="CL"]
                  + fire[vegetation=="CL"] + deforestation_driver[vegetation=="CL"]
                  + precipitation[vegetation=="CL"] + tree_cutting[vegetation=="CL"],
                  data=rfdataset, ntree = 601, proximity = TRUE, importance = TRUE,
                  type = regression)

modelrfsprcl

print(modelrfsprcl)

varImpPlot(modelrfsprcl)

importance(modelrfsprcl)

varUsed(modelrfsprcl)
```

A.2.1.9 Method to remove remnant biomass

To exclude biomass that accumulated prior to the regeneration time, the maximum potential dbh of all stems was calculated as the product of regeneration time (Section 2.8) and maximum growth rates, 3.55 cm y^{-1} for *Vachellia tortilis* trees and 1.93 cm y^{-1} for other species based on the *Brachystegia spiciformis* rate (Backéus et al 2022). If the dbh of a stem exceeded the maximum potential dbh plus a 2 cm buffer, it was considered a remnant stem and only the calculated maximum potential dbh was used for that stem. There were 119 remnant trees in 51 FSSPs out of a total of 9,757 trees in the 180 FSSPs, including three *V. tortilis* trees.

Appendix 2.2 Results

A.2.2.1 Proportion of village land following different land cover change trajectories between 1987 and 2021

Land cover change class	Percentage of village land (95% Confidence Interval)	Equivalent area (hectares) (95% Confidence Interval)
Forest / woodland / bushland remains as forest / woodland / bushland	41.4% (37.04%-45.86%)	23,306,245 (20,854,411-25,815,663)
Agriculture remains as agriculture	21.0% (17.51%-24.84%)	11,822,008 (9,857,427-13,981,934)
Plantation remains as plantation	0.6% (0.12%-1.74%)	337,772 (69,753-981,434)
Agriculture converts to plantation and then converts to agriculture	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)
Agriculture converts to forest / woodland / bushland then converts to agriculture then converts to forest / woodland / bushland and then converts to agriculture	0.4% (0.05%-1.44%)	225,181 (27,291-809,193)
Agriculture converts to forest / woodland / bushland and then converts to agriculture	1.4% (0.56%-2.86%)	788,134 (317,886-1,611,825)
Forest / woodland / bushland converts to agriculture with no regeneration	18.8% (15.47%-22.51%)	10,583,512 (8,707,917-12,669,579)

Land cover change class	Percentage of village land (95% Confidence Interval)	Equivalent area (hectares) (95% Confidence Interval)
Forest / woodland converts to agriculture and then to plantation	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)
Forest / woodland / bushland converts to other	0.8% (0.22%2.04%)	450,362 (122,944-1,145,926)
Forest / woodland / bushland converts to agriculture and then converts to forest / woodland / bushland and then converts to agriculture	2.4% (1.25%-4.15%)	1,351,087 (701,509-2,338,935)
Forest / woodland / bushland converts to agriculture and then converts to forest / woodland / bushland	4.4% (2.78%-6.59%)	2,476,992 (1,563,701-3,707,663)
Forest / woodland / bushland converts to agriculture and then converts to forest / woodland / bushland and then to agriculture and then to forest / woodland / bushland	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)
Forest / woodland / bushland converts to grassland then converts to forest / woodland / bushland	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)
Agriculture converts to forest / woodland / bushland	0.8% (0.22%-2.04%)	450,362 (122,944-1,145,926)
Agriculture converts to other non-forest land cover	1.4% (0.56%-2.86%)	788,134 (317,886-1,611,825)
Agriculture converts to wetland	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)

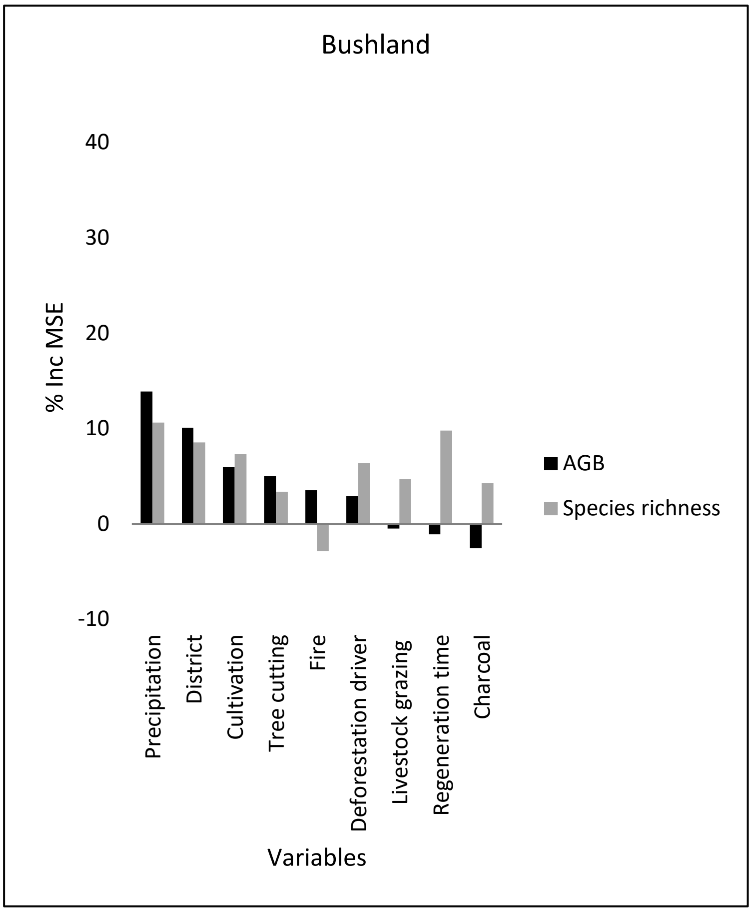
Land cover change class	Percentage of village land (95% Confidence Interval)	Equivalent area (hectares) (95% Confidence Interval)
Wetland converts to forest / woodland / bushland then to agriculture	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)
Grassland converts to agriculture	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)
Grassland remains as grassland	2.8% (1.54%-4.65%)	1,576,268 (866,418-2,619,607)
Other non-forest land cover remains as other non-forest land cover	2.2% (1.10%-3.90%)	1,238,496 (621,065-2,196,785)
Wetland converts to agriculture then back to wetland	0.2% (0.01%-1.11%)	112,591 (2,850-624,454)
Total study area		**56,295,277**

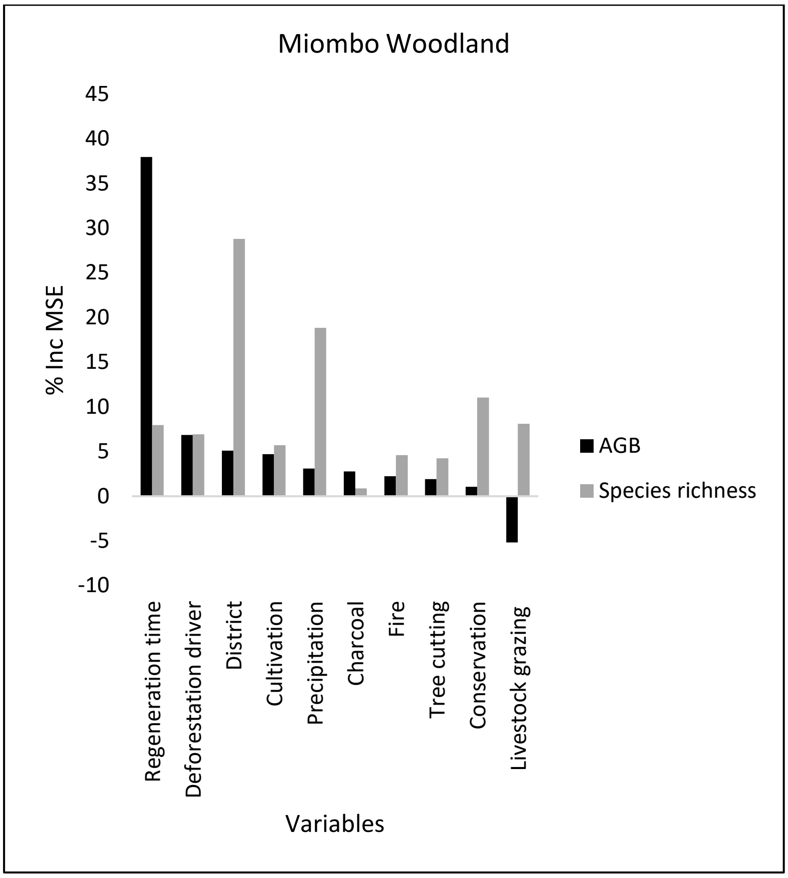
A.2.2.2 Field survey locations

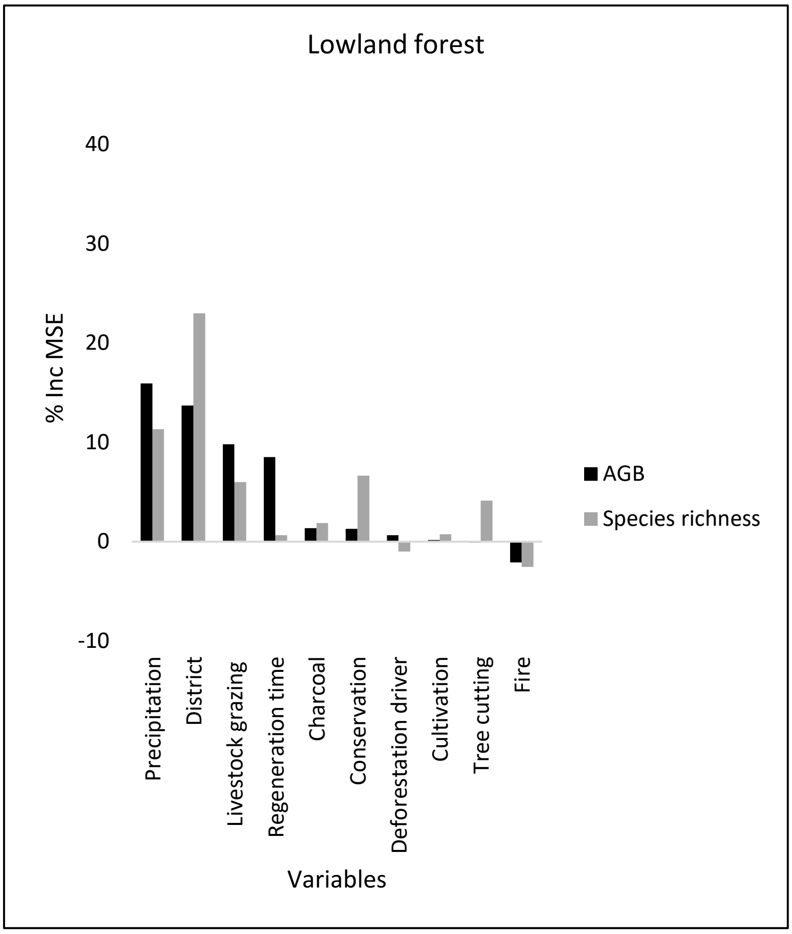
District	Min altitude	Max altitude	Number of plots per vegetation class					Mean annual precipitation	Central coordinates for field survey sites	Distance between most distant survey points
	m asl	m asl	BA	BT	CL	MW	Total	mm	longitude, latitude	km
Kasulu	1292	1477	0	0	0	17	17	1217	30.2875, -4.3512	5.8
Kilindi	672	764	0	0	19	0	19	950	37.8996, -5.4662	15.4
Masasi	558	844	0	0	7	13	20	1087	39.0861, -10.6662	5.4
Manyoni	1120	1240	8	6	4	0	18	582	34.8558, -6.2002	22.8
Mpimbwe	848	1005	17	0	0	0	17	943	31.2408, -7.1256	34.8
Mvomero	288	501	12	0	6	0	18	929	37.6314, -6.2623	73.5
Namtumbo	762	976	0	0	0	18	18	1308	36.0082, -10.2909	36.8
Tunduru	596	760	0	0	2	17	19	1066	37.1533, -11.2327	11.4
Ushetu	1100	1242	0	0	6	11	17	835	32.1641, -4.1132	15.8
Uvinza	1051	1133	0	0	7	10	17	993	31.0437, -5.1678	23.6
Total			**37**	**6**	**51**	**86**	**180**			

A.2.2.3 Results of the random forest regression models for above ground biomass and species richness

Influence of variables (% increase in the mean-squared error of the random forest regression model, if the variable is excluded) on above ground biomass (including stumps, excluding remnant trees) and species richness for plots disaggregated by vegetation type into bushland, miombo and lowland forest




Miombo Woodland
45
40
35
30
25
20
15
10
5
0
-5
-10
% Inc MSE
Regeneration time
Deforestation driver
District
Cultivation
Precipitation
Charcoal
Fire
Tree cutting
Conservation
Livestock grazing
Variables
AGB
Species richness


Lowland forest
40
30
20
10
0
-10
% Inc MSE
Precipitation
District
Livestock grazing
Regeneration time
Charcoal
Conservation
Deforestation driver
Cultivation
Tree cutting
Fire
Variables
AGB
Species richness

A.2.2.4 Forest cover change data

Data will be / are available as supplementary material to the published version.

Appendix 2.3 References for Appendix 2

Backéus I Skoglund J Skarpe C and Hytteborn H 2022 Diameter growth of trees in miombo and acacia woodland in an eroded landscape in NE Tanzania. Afr J Ecol aje.12970. https://doi.org/10.1111/aje.12970

Shimada, M., Itoh, T., Motooka, T., Watanabe, M., Shiraishi, T., Thapa, R., Lucas, R., 2014. New global forest/non-forest maps from ALOS PALSAR data (2007–2010). Remote Sensing of Environment 155, 13–31. https://doi.org/10.1016/j.rse.2014.04.014

Appendix 3 Supplementary material for Chapter 5

Appendix 3.1 Results

Supplementary Table 7 List of policy documents and government reports reviewed for Chapter 5

EWURA. 2011. Energy and Water Utilities Regulatory Authority Annual Report 2010/11. Dar es Salaam, Tanzania.

EWURA. 2012. Energy and Water Utilities Regulatory Authority Annual Report 2011/12. Dar es Salaam, Tanzania.

EWURA. 2016. Energy and Water Utilities Regulatory Authority Annual Report 2015/16. Dar es Salaam, Tanzania.

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EWURA. 2018. Downstream petroleum sub-sector performance review report for year 2017. Dar es Salaam, Tanzania.

National Bureau of Statistics (NBS) (Tanzania) 2002. Tanzania Household Budget Survey 2000/01. Dar es Salaam, Tanzania: NBS.

National Bureau of Statistics (NBS) (Tanzania) 2005. Tanzania Demographic and Health Survey 2004 / 5.

National Bureau of Statistics (NBS) (Tanzania) 2009. Tanzania Household Budget Survey 2007 Final Report. Dar es Salaam, Tanzania: NBS.

National Bureau of Statistics (NBS) (Tanzania) 2014a. Tanzania Household Budget Survey 2011/12. Main Report. Dar es Salaam, Tanzania: NBS.

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National Bureau of Statistics (NBS) (Tanzania), 2014c. Tanzania National Panel Survey Report (NPS) - Wave 3, 2013-2013. Tanzania National Bureau of Statistics, Dar es Salaam.

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United Republic of Tanzania, 2015. Intended Nationally Determined Contributions under the Paris Agreement.

United Republic of Tanzania, 2016. Power system master plan. 2016 update. 139 pp.

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United Republic of Tanzania – Ministry of Energy and Minerals, 2015. Tanzania's Sustainable Energy for All Action Agenda. https://www.seforall.org/sites/default/files/TANZANIA_AA-Final.pdf

United Republic of Tanzania – Ministry of Energy and Minerals, 2016. Power System Master Plan – 2016 Update. Downloaded from https://www.nishati.go.tz/useful-documents/ 20/10/2018

United Republic of Tanzania – Ministry of Energy and Minerals, 2016. Natural gas utilisation master plan 2016 – 2045. Draft.

United Republic of Tanzania - Ministry of Natural Resources and Tourism. 2010 Report of the Task Force on Improving Revenue Collection in The Ministry of Natural Resources and Tourism. Volume i: Main Report.

United Republic of Tanzania - Ministry of Natural Resources and Tourism. 2012. Participatory Forest Management: Facts and Figures.

United Republic of Tanzania - Ministry of Natural Resources and Tourism. 2015. National forest Resources Monitoring and Assessment of Tanzania Mainland: Main Results.

United Republic of Tanzania - Ministry of Natural Resources and Tourism. 2018. Hotuba ya Waziri wa Maliasili na Utalii Mheshimiwa dkt. Hamisi a. Kigwangalla (mb), wakati akiwasilisha bungeni makadirio ya mapato na matumizi kwa mwaka wa fedha 2019/2020. http://www.tfs.go.tz/uploads/natural_forests/Hotuba_ya_Bajeti_Wizara_ya_Maliasili_na_Utalii.pdf

United Republic of Tanzania, 2010. Tanzania Forest Services Agency Framework document. 26p: TFS, Dar-Es-Salaam, Tanzania

United Republic of Tanzania, 2012. Tanzania Forest Services Agency Annual implementation report (2011/2012), 27p; TFS, Dar-Es-Salaam, Tanzania

United Republic of Tanzania, 2013a. Tanzania Forest Services Agency Annual implementation report (2012/2013), 21p; TFS, Dar-Es-Salaam, Tanzania

United Republic of Tanzania, 2014a. Tanzania Forest Services Agency Annual implementation report (2013/2014), 31p; TFS, Dar-Es-Salaam, Tanzania

Appendix 3.2 Data availability

The dataset for Chapter 5 is available at:

https://www.sciencedirect.com/science/article/pii/S0973082620302556#ec0005

Appendix 4 Policy Briefs

Policy Brief

UNIVERSITY OF LEEDS

Charcoal in Tanzania: the persistently popular cooking-fuel in need of a policy re-think

Issue date
July 2020

Key Messages

- Demand for charcoal has increased in Tanzania's largest city, Dar es Salaam, over the last 30 years.
- Total demand for charcoal in Tanzania is likely to increase for the foreseeable future.
- National energy policy has sought to transition households away from charcoal use, with limited success.
- Charcoal is popular in Tanzania because it is cheap and reliable.
- Widespread non-payment of charcoal royalties contributes to charcoal being cheaper than other cooking fuels.

Charcoal in Tanzania

For decades policy-makers have sought to reduce charcoal use in Tanzania. However, it remains the most popular cooking fuel for urban households. Understanding charcoal's persistent popularity is helpful in designing policies to align the charcoal trade more closely with Tanzania's development priorities.

Charcoal's advantages are that it is affordable, reliable, and is produced in-country providing employment for tens of thousands of producers and traders. Charcoal has the potential to generate substantial government revenues. However, charcoal also has disadvantages. Charcoal causes health problems and contributes to deforestation and forest degradation. There is widespread evasion of charcoal royalty payments.

The study described in this policy brief looks at how policies have influenced the charcoal trade and whether policy change could achieve outcomes aligned with Tanzania's development priorities.

In the energy sector, successive national energy policies have sought to transition urban households away from charcoal and into modern fuels (e.g. liquefied petroleum gas (LPG)). In keeping with this policy and in order to make LPG more competitive, LPG has been exempted from the fuel levy, foregoing over US$40 million in revenue annually. On the supply side, forest policy has sought to regulate the charcoal trade and generate government revenue from royalties. Policies have not encouraged sustainable charcoal production from natural woodlands and there have been few attempts to produce charcoal sustainably.

Understanding how national policies influence households' cooking-fuel use

In late 2018, household surveys were carried out involving 100 randomly-selected households across Tanzania's largest city, Dar es Salaam. Data were collected on the different types of fuel used for cooking; why households prefer different fuels; and fuel costs.

Through surveys with charcoal retailers, traders and producers, data were also collected on charcoal prices along the value chain. By comparing this information with the results of previous surveys and with information on government taxes, royalties and other fees, it was possible to link fuel-use trends with policy shifts. Price data for other cooking fuels were collected and compared with charcoal prices per unit of usable energy.

Photo by Rob Beechey

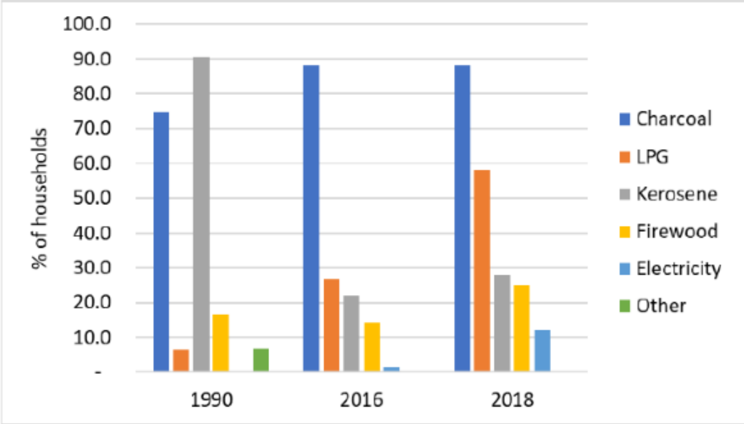

Figure 1. Changes in the percentage of households using five cooking-fuels in Dar es Salaam between 1990 and 2018. Source: Doggart et al.

Key findings of the survey

1. **Urban households have not transitioned from charcoal to modern cooking fuels**, over the last 30 years. A higher proportion of Dar es Salaam households used charcoal in 2018, than in 1990 (Fig. 1). Charcoal has remained popular despite three successive energy policies promoting a transition to modern fuels.
2. **Demand for charcoal in Dar es Salaam has quadrupled** from 0.22 million tonnes in 1990 to 0.94 million tonnes in 2018. Increased charcoal demand is largely driven by population growth and urbanisation.
3. **Charcoal is popular because it is cheaper than other fuels**, including LPG. Only firewood is cheaper, per unit of energy. Widespread non-payment of charcoal royalties contributes to the low cost of charcoal.
4. **Policy interventions have influenced cooking-fuel choices, primarily by impacting fuel cost.** For example, less households used kerosene in 2018 than in 1990, due to a fuel levy increase on kerosene in 2011, making it more expensive. In contrast, LPG's popularity increased due to a fuel levy exemption in 2015. However, more LPG use has not resulted in less charcoal use (Fig. 1).
5. **Government revenue from royalties on the charcoal used in Dar es Salaam should exceed US$ 98 million.** In practice, less than 10% of this is collected.
6. **Current policies do not promote sustainable, efficient and safe charcoal production and use.** Charcoal is excluded from the scope of the National Energy Policy.
7. **Most households in Dar es Salaam use more than one fuel.** On average, households use 2.1 fuels for cooking. An LPG/charcoal combination is most popular.

Recommendations

1. Embrace charcoal into national policy

Based on historical trends, charcoal will continue to be used by most urban households for the foreseeable future. Changing energy and forestry sector policies to reflect the continued popularity of charcoal, could achieve outcomes aligned with the national development vision of building a strong and resilient economy. Relevant policy options include: supporting sustainable charcoal production in community-managed woodlands; reducing the health impacts of charcoal use, through promotion of low-emission stoves and safer cooking practices; and building technical expertise along the value chain.

2. Re-evaluate the fuel-levy exemption on LPG

Fiscal tools have influenced consumer demand for LPG and kerosene. In the case of LPG, the rationale for exempting LPG from the fuel levy was to reduce deforestation and household air pollution by encouraging households to replace charcoal with LPG. With little evidence that the broader objectives of the exemption have been achieved, it would be worthwhile to re-evaluate the exemption.

3. Support research and monitoring of charcoal

Policy-relevant research on charcoal's contribution to the economy, sustainable production options and safer production and use options, is needed.

This policy note is based on: Doggart, N., Ruhinduka, R., Meshack, C.K., Ishengoma, R.C., Morgan-Brown, T., Abdallah, J.M, Spracklen, D.V. & Sallu, S.M. 2020. The influence of energy policy on charcoal consumption in urban households in Tanzania. *Energy for Sustainable Development*. Available for free download at https://doi.org/10.1016/j.esd.2020.06.002

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POLICY BRIEF

Tanzania Forest Conservation Group
Shirika la Kuhifadhi Misitu ya Asili Tanzania

UNIVERSITY OF LEEDS

DRIVERS OF DEFORESTATION IN TANZANIA

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Key Messages

- Most deforestation in Tanzania is caused by small-scale agriculture, particularly maize cultivation.
- Charcoal production, pole cutting and timber harvesting often take place during the process of deforesting an area for agriculture but are primarily drivers of forest degradation, rather than deforestation.
- More deforestation occurs on village land than in forest reserves and other protected areas.
- Scaling-up community-based forest management, the main policy tool designed to protect forests on village land, could contribute to reducing deforestation.

FORESTS AND DEFORESTATION IN TANZANIA

Forests are vital to Tanzania's economic and social development. Forests provide:

- environmental services including protection of water sources, soil, biodiversity and climate; and
- forest products including wood fuel, timber, medicinal plants and forest foods.

Tanzania is undergoing a period of rapid deforestation. Every year, more than half a million hectares of forest are cleared[1].

Deforestation involves the conversion of forest land to non-forest land. Deforestation threatens the supply of forest ecosystem services and products.

In order to reduce deforestation, it is important to understand the drivers of deforestation. Drivers of deforestation are the human activities that cause forest loss. To be effective in reducing deforestation, policies need to tackle the activities that cause the most forest loss.

In 2017, Tanzania had approximately 37.7 million hectares of forest. Of this, 41% is protected in areas such as forest reserves while 45% is on village land, managed by communities[2]. Unreserved forests on village land are the most threatened.

PUTTING A FIGURE ON HOW MUCH DEFORESTATION IS CAUSED BY DIFFERENT DRIVERS

In order to generate policy-relevant information on how to reduce deforestation, a study was carried out in 2018/19 to measure the relative importance of different deforestation drivers[1].

The study mapped the area of land that was deforested between 2010 to 2017, across Tanzania and then surveyed 120 random sampling points from the deforested area. Each sampling point was assessed in order to identify the activities that had contributed to the clearance of the forest.

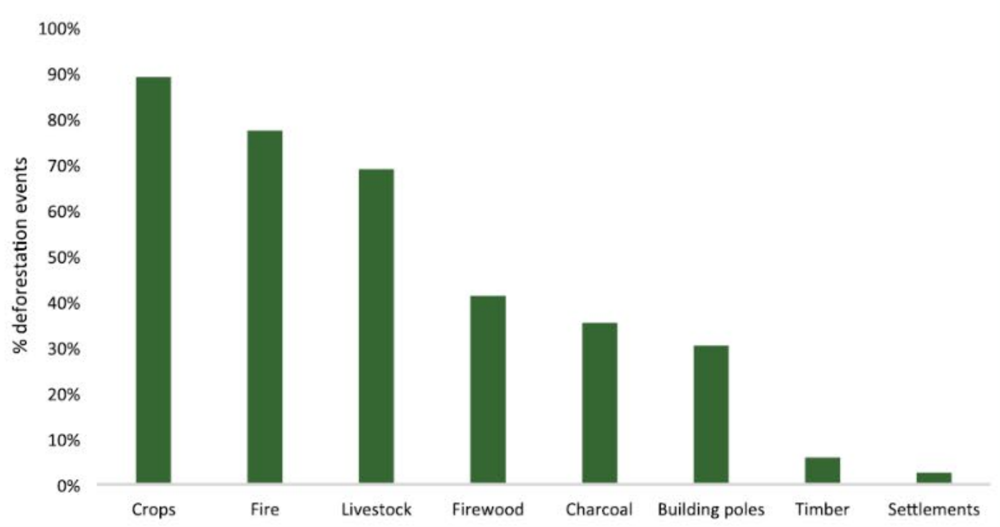
All activities were measured including both drivers of deforestation and drivers of forest degradation. The surveys used a combination of satellite images, field visits and interviews with local people.

Deforestation driver: an activity that causes the conversion of forest land to non-forest land e.g. agriculture.

Forest degradation driver: an activity that causes loss of forest quality, such as reduced tree density, in areas that remain forest e.g. charcoal production, firewood collection

1 Doggart et al. 2020 doi.org/10.1088/1748-9326/ab6b35
2 Source: MNRT, 2015 National Forest Resources Monitoring and Assessment of Mainland Tanzania: main report.

Figure 1. Percentage of deforestation events where drivers of deforestation and forest degradation were present.



Source: Doggart et al. 2020

WHICH ACTIVITIES CAUSE MOST DEFORESTATION?

Key findings of the survey

1. Small-scale agriculture is the main driver of deforestation in Tanzania and was recorded in 89% of the deforested areas (Figure 1).
2. Over half of all deforestation events (57%) involve maize cultivation. Sesame is also associated with deforestation (20% of events).
3. Most deforestation events involve multiple drivers, most frequently a combination of crops and livestock.
4. Firewood collection, charcoal production and pole-cutting contributed to 30% - 40% of deforestation events, always in combination with either crops, or livestock grazing.
5. Charcoal was never found to drive deforestation separately from crops or livestock.
6. Fire is frequently used to clear forest, with signs of fire evident in 77% of deforested areas.

RECOMMENDATIONS

Given that most deforestation is caused by agriculture, there is a need to focus on changing the relationship between farmers and forests.

In the agriculture sector, change is needed to:
- reduce farmers' dependence on expanding farms into intact forest areas;
- avoid policies that incentivise or encourage farmers to clear natural forest;
- provide support and incentives to forest managers and forest owners to retain natural forest, rather than converting land to agriculture.

In forestry, community-based forest management (CBFM) is the main policy tool to protect forests on village land. CBFM empowers communities to establish and manage village forest reserves. With <10% of village land forests under CBFM currently, the opportunity exists to expand CBFM.

Given that most deforestation involves more than one activity, reducing deforestation requires strong inter-sectoral coordination between the land, agriculture, livestock and forest sectors.

This policy note is based on: Doggart, N., Morgan-Brown, T., Lyimo, E., Mbilinyi, B., Meshack, C.K., Sallu, S.M., Spracklen, D.V., 2020. Agriculture is the main driver of deforestation in Tanzania. *Environmental Research Letters* **15**

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