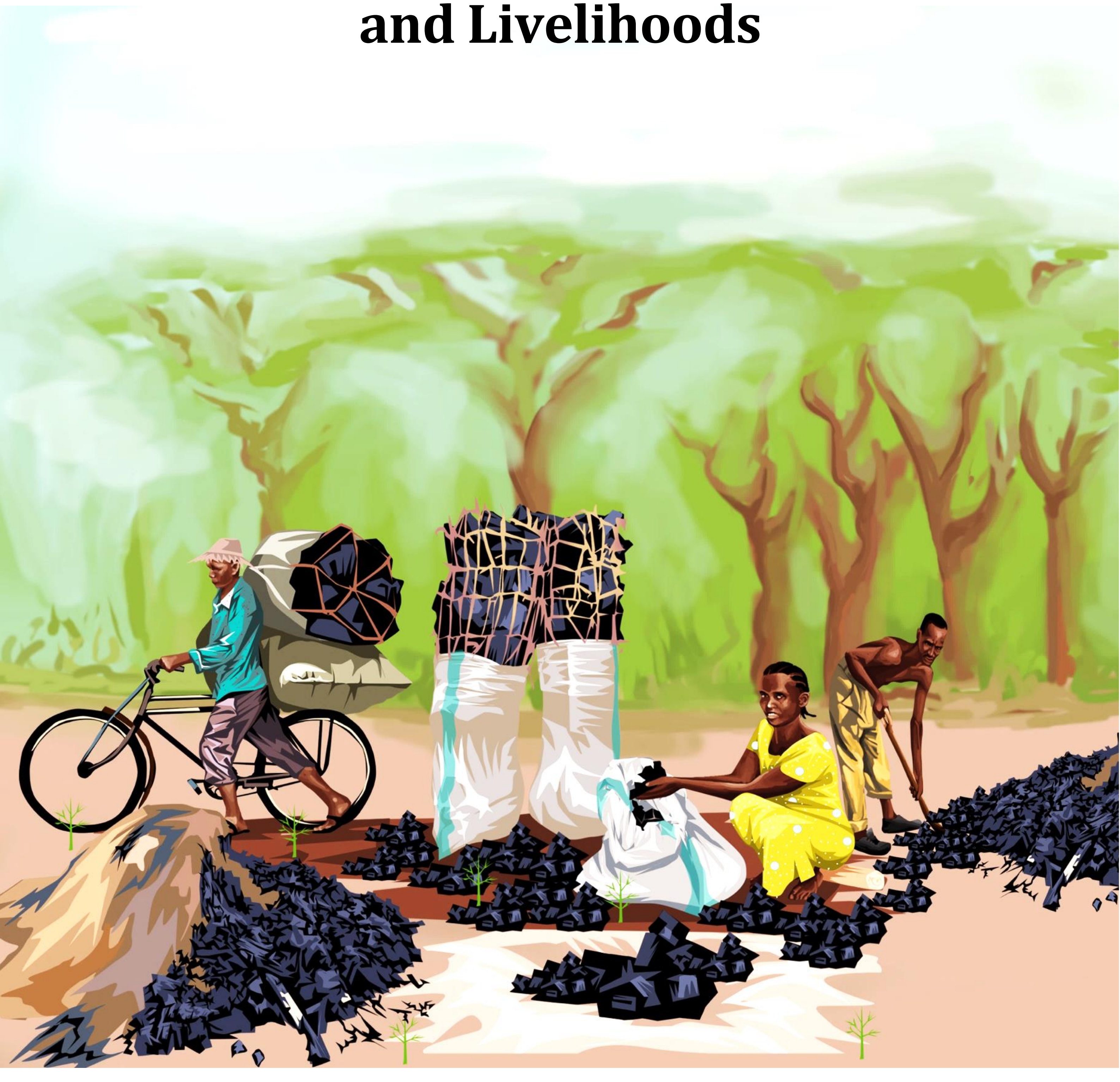
# Effects of Transitions in Charcoal Production Systems on Forests and Livelihoods



Hanneke van ‘t Veen
2022

# Effects of Transitions in Charcoal Production Systems on Forests and Livelihoods

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# Abstract

People around the world rely on products from nature to sustain their livelihoods but human-induced pressures strongly affect the Earth's natural resources, causing unprecedented loss of ecosystem services. Charcoal, a biomass-based renewable energy produced from woody biomass, is one of these products from nature which provides an important income and energy source for hundreds of millions of people but simultaneously causes forest degradation and up to 7% of deforestation globally. To mitigate overexploitation of forests, transitions in charcoal production systems from unregulated charcoal production under limited adherence to existing rules and regulations (i.e., open access) to more regulated production through governance of forest by local communities (i.e., through communal management) or privately by individuals or companies (e.g., through privatization) are necessary. In this thesis, we assess effects of transitions in charcoal production systems from open access systems to private and, in particular, communal management systems on forest use and livelihoods through stylized modelling (**Chapter 3**), remote sensing (**Chapter 4** and **Chapter 5**), livelihood analyses (**Chapter 6** and **Chapter 7**), and a global assessment of governance effects on charcoal production (**Chapter 8**). We use the social-ecological systems framework and the eight design principles of Elinor Ostrom for sustainable management of common pool resources as guideline to organize and discuss our findings. In **Chapter 3**, we find that charcoal production system transitions are unnecessary at low demand but that transitions to communal management (at medium to high forest biomass availability) and private systems (at low forest biomass availability) are necessary to prevent a collapse of forest resources and subsequently of charcoal production. To empirically test our stylized modelling results, we conducted local field studies in six study villages in Kilosa district, Tanzania, three of which under open access and three of which under communal management. This case study informed **Chapter 4** to **Chapter 7** of this thesis. A comparison of forest use and livelihoods in the two village types informs us about the potential social-ecological consequences of transitioning from open access to communal management systems and vice versa. We find significant differences in forest use and access of charcoal producers to livelihood resources (i.e., livelihood capitals) between the two village types, indicating that governance has the potential to shape forest use and livelihoods. Yet, we find mismatches between the objectives of the communal management scheme in place and reality – we observe production outside of forest areas designated for charcoal production. This mismatch may result from a trade-off observed between financial capital in the form of income per charcoal bag and other livelihood capitals under communal management, resulting from a revenue-sharing scheme that transforms financial capital into other capitals that benefit both individual charcoal producers and the community they are part of. This trade-off may potentially increase charcoal production in communal management villages, causing charcoal producers to move outside designated areas for production to obtain enough income to sustain their livelihoods. Besides this, **Chapter 8** reveals that development (i.e., human well-being), rather than forest governance, influences charcoal production on a global scale. Altogether, our results suggest that governance transitions have the potential to foster sustainable forest use and livelihoods in charcoal production systems but that challenges remain in the percolation of governance goals at both local and national scales.

# Summary

Humanity relies on products from nature to sustain their livelihoods. Yet, human-induced pressures strongly affect the Earth system, reducing its natural resources and causing unprecedented loss of ecosystem services, such as biodiversity and carbon sequestration. To simultaneously foster sustainable livelihoods and sustainable use of natural resources, it is vital to understand the ways in which existing policies and governance systems affect them. Social-ecological system theory allows us to better understand interactions between natural resources and society by identifying relevant interrelated social and ecological components and design principles that promote sustainable management of social-ecological systems. In this thesis, I take a look at social and ecological components and the ways they are influenced by existing policies and governance in order to understand the social-ecological dynamics of one specific social-ecological system, the charcoal production system.

Charcoal producers in tropical biomes carbonize woody biomass from forests or plantations to derive charcoal, which is then sold to fulfill energy demands of hundreds of millions of households and of industry. Charcoal production provides an important income source and livelihood diversification opportunity for charcoal producers, allowing them to pay for health care, education and other vital livelihood assets (i.e., livelihood capitals). However, charcoal production also causes 7% of deforestation and forest degradation, largely as by-product of agricultural expansion. This results in a loss of biodiversity, carbon emissions and other forest-related ecosystem services. A predicted 5% increase in charcoal production by 2100 likely enforces this. Yet, biomass-based renewable energies, including charcoal, have the potential to be carbon neutral or even carbon positive. Therefore, there is a need to foster transitions that allow for a continuation of charcoal production and the important livelihood benefits it provides, while mitigating the forest degradation and deforestation it causes. Such transitions, include governance transitions through the implementation of a (new) set of laws, rules and regulations, e.g., to foster inclusive and community-based regulation of charcoal production. In this thesis, I explore effects of transitions in charcoal production systems on social and ecological components of charcoal production systems and their interactions through the following three overarching research questions on forest use, livelihoods and governance:

1. What is the spatiotemporal effect of transitions in charcoal production systems on forest use?
2. What is the effect of transitions in charcoal production systems on the livelihoods of charcoal producers?
3. What is the effect of forest governance on charcoal production and forests?

Following the general introduction of **Chapter 1**, I first identify the most common charcoal production systems in **Chapter 2**, before answering the above research questions. In **Chapter 2**, I explore six charcoal production systems, of which two are under open access, two under communal management, and two are private systems. In open access systems, charcoal producers relatively freely extract forest resources to produce charcoal and show limited adherence to rules and regulations for charcoal production. In communal management systems forest resources for charcoal production are managed collaboratively by communities, such as villages, in pursuit of sustainable forest extraction and livelihoods. In private systems, individuals or companies have rights over the forest or plantation resources they own or tend for, making them the primary managers of these resources.

In **Chapter 3**, I assess effects of governance transitions from open access systems to communal management and private systems through stylized social-ecological modelling. I find that governance transitions are unnecessary at low demand in open access systems, while at medium to high demand, governance transitions to either communal management or private systems can assure long term sustainability of production within 100 years. I conclude that transitions to communal management systems are most effective at medium to high forest availability, as this assures production levels that sustain livelihoods. Transitions to private systems appear more favorable at low forest biomass availability, provided that plantation resources are available and allow for a continuation of production.

To test dynamics between forest resources and livelihoods in reality, I conducted empirical research in six study villages in Kilosa district of Tanzania, which informed **Chapter 4** to **Chapter 7** of this thesis. Three of these villages are under open access, while the other three are under communal management. In **Chapter 4**, I develop a remote sensing method to detect charcoal production sites. Detection of charcoal sites is challenging because they consist of different features of different shapes and sizes, including harvesting areas, and kilns/kiln scars, (remains of) carbonization ovens in which charcoal production takes place. Besides this, charcoal sites are covered by different levels of canopy cover because tree cutting practices range from clear cutting, characterized by the removal of all trees in the harvesting area, and selective cutting, characterized by the removal of selected trees according to the quality of charcoal they produce or harvesting guidelines. To allow for the detection of these variable landscape features, I combine three remote sensing methods to detect charcoal production sites, namely one classification method for Landsat-8, one classification method for Sentinel-2, and one visual imagery inspection method. Each of these methods takes advantage of the reflection from different components of charcoal production sites. I conclude that the three methods combined allow for robust identification of charcoal production sites.

The large variations in spatial characteristics and arrangement of observed charcoal sites in **Chapter 4** can affect forest dynamics, such as forest regeneration and biodiversity. In **Chapter 5**, I use the results from **Chapter 4** to examine effects of social-ecological drivers on landscape patterns of charcoal sites in our study area, including their size, shape, density and distribution. This provides is a first step towards the spatial modelling of charcoal production in response to social-ecological drivers, which may allow for impact assessments on forest regeneration, carbon stocks and biodiversity in the future. I find that charcoal site patterns are affected by governance regime, i.e., with significantly smaller, more regularly shaped sites in communal management than open access systems. While this may suggest a general adherence to the proposed harvesting guidelines, the results also show that charcoal production prevails outside of designated forest areas specified in communal management harvesting plans. In fact, only 16.04%, 10.00%, and 9.72% of detected charcoal sites were found inside of designated forest areas for charcoal production in the three communal management villages. This suggests a potential mismatch between the governance goals of communal management and reality. In open access villages, a combined effect of travel distance to village centers and aboveground biomass availability drives charcoal production patterns in the landscape, resulting in characteristic peaks in charcoal site numbers and sizes at specific distances from the village center. I conclude that governance as a driver has the power to shape charcoal production patterns in the landscape but that challenges in fostering forest management in line with harvesting plans remain.

To differentiate reasons for a potential mismatch between the communal management harvesting plan and charcoal production practices in communal management systems, I examine the livelihood capitals of charcoal producers in **Chapter 6** and **Chapter 7.** As communal management requires collaborative management of the forest, it is important to foster dense social networks between charcoal producers and between members of their governments, allowing for knowledge exchange, trust, reciprocity and a sharing of norms and values, which theoretically fosters high quality forest governance. In **Chapter 6**, I explore the social networks of charcoal producers in the six study villages, using information acquired through 160 livelihood surveys. I find significantly denser and more decentralized social networks in communal management systems than in open access systems, indicating that governance transitions to communal management systems realized the goal of enhancing collaboration. I find that this is mainly relates to a formalization of interactions under communal management through training sessions for sustainable charcoal production, charcoal producer associations and a participatory decision-making process. I conclude that the continuation of formal institutions, such as committees, associations and training sessions, is vital in fostering the active collaboration required to uphold sustainable communal forest management.

**Chapter 6** provides insight into the impact of governance transitions on one important livelihood resource of charcoal producers, social capital. In **Chapter 7**, I put the findings of **Chapter 6** in perspective by examining the access of charcoal producers to a multitude of livelihood capitals needed to foster a sustainable livelihood. These include natural capital (i.e., forest resources), human capital (i.e., knowledge and health), financial capital (i.e., income and charcoal production), and physical capital (i.e., physical assets, such as housing), using data from the same 160 livelihood surveys, which we transformed into 19 livelihood capital indicators. I assessed the synergies and trade-offs that emerge between indicators for all livelihood capitals derived from the livelihood surveys. I then compared these trade-offs and synergies between villages under open access and under communal management, shedding light on the capacity of governance to foster sustainable livelihoods by providing access to all livelihood capitals. I find that transitions to communal management have the power to enhance access of charcoal producers to specific aspects of livelihood capitals (i.e., specific livelihood indicators), in particular those of natural, social and to a certain extent human capital. Nevertheless, I find indications that fostering access to these capital aspects may be at the expense of other livelihood capitals, in particular the income charcoal producers receive per bag of charcoal. A likely explanation for this is that part of the income per bag is shared in a community fund, which invests in forest management and community development, hereby provide livelihood capital access in the form of human, social, physical and natural capital to individual charcoal producers and the communities they are part of. Additionally, I find many trade-offs and synergies between indicators of the same livelihood capital for both open access and communal management systems. This suggests that livelihood capitals are not singular and that fostering enhanced access to one aspect of a livelihood capital does not automatically increase access to other aspects; in fact it may negatively affect them. I conclude that our study highlights opportunities to foster sustainable livelihoods through governance transitions to communal management, although this is challenged by complex synergies and trade-offs between livelihood capitals.

**Chapter 6** and **Chapter 7** highlight the value of formalized institutions to assure collaborative forest management. Currently, many countries face challenges in top-down percolation of governance goals, which challenges the successful up-scaling of governance transitions that induce formalized communal management. Hence, positive effects of governance on forest use and livelihoods locally, may not translate to national and international scale. To explore governance at larger spatial scales, I assess effects of different governance regimes of various quality on charcoal production and deforestation in governance systems of all tropical countries around the world in **Chapter 8**. I find that governance quality only weakly affects charcoal production. Rather social-economic settings of countries (i.e., their development status) influence charcoal production and governance quality alike, creating a divide between African countries, were charcoal production is high and Asian and South American countries, were charcoal production is lower. Nevertheless, I find indications that regional governing bodies (e.g., districts or provinces) may foster higher governance quality and lower charcoal production, likely because they form a bridge that allows for effective communication between national governing bodies (e.g., ministry of environment) and local governing bodies (e.g., village government). I conclude that our study provides a first step to identify forest governance systems that allow for effective regulation of charcoal production and the mitigation of deforestation.

In the synthesis of this thesis, I conclude that transitions in charcoal production systems have the power to change forest use and livelihoods, in particular transitions to communal management. Nevertheless, challenges remain in the percolation of governance goals at both local and global scale, as well as in the continuation of specific attributes of governance systems that foster livelihood sustainability, such as charcoal producer associations. Social-ecological system theory and design principles for sustainable management of natural resources provide a useful frame to explore interrelations between forests, livelihoods and governance to put the findings of this thesis in perspective of wider social-ecological system science.

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# Scientific papers

Scientific papers written for this thesis and their publication status at the time of thesis submission, April 2022:

| | |
|---|---|
| **Chapter 3** (*published*) | van 't Veen, H., M.B. Eppinga, T.H. Mwampamba, and M.J. Santos. 2021. “Long term impacts of transitions in charcoal production systems in tropical biomes.” *Environmental Research Letters* 16 (3): 034009. https://doi.org/10.1088/1748-9326/abe14d |
| **Chapter 4** (*in review*) | van ’t Veen, H., D. Villamaina, W. Mugasha, C.K. Meshack and M.J. Santos. *In review*. “Detecting charcoal production sites using a combined remote sensing approach with Landsat-8, Sentinel-2 and VHR data.” *Remote Sensing of Environment*. |
| **Chapter 5** (*in progress*) | van ‘t Veen, H., M.B. Eppinga, M.J. Santos. *In progress*. “Understanding social-ecological processes driving charcoal production patterns at a landscape scale.” This paper will be submitted to *Landscape Ecology* after acceptance of the paper written for Chapter 4. |
| **Chapter 6** (*submitted*) | van ‘t Veen, H., V.G. Vyamana, C.K. Meshack, J.H. Jengo, M.S. Mpembela and M.J. Santos. *Submitted*. “Effects of governance transitions on charcoal producer social networks.” *Sustainability Science*. |
| **Chapter 7** (*submitted*) | van ‘t Veen, H., V.G. Vyamana and M.J. Santos. *Submitted*. “Effects of forest governance on synergies and trade-offs in charcoal producer livelihoods.” *Energy for Sustainable Development*. |
| **Chapter 8** (*published*) | van 't Veen, H., V.G. Vyamana and M.J. Santos. 2022. “Forest governance and development effects on tropical charcoal production and deforestation.” *Environmental Research Letters* 17: 024040. https://doi.org/10.1088/1748-9326/ac462d |

# Chapter 1

## General introduction

You and me, like all humans around the world depend on resources from nature and its biodiversity to fulfill our livelihoods, i.e., activities we carry out to fulfill our basic daily needs (Ostrom 2009, Scoones 1998). To fulfill these needs, humans exploit, tend for and promote the growth of natural resources under formal and informal laws, rules and regulations of communities, states, nations and the world (Loft *et al* 2015, Primmer *et al* 2015). On its turn, ecosystems provide natural resources, which have their own dynamic growth rates and biodiversity (Gounand *et al* 2020, Loreau *et al* 2001), currently affected by land use change (de Chazal and Rounsevell 2009), overexploitation (Mora *et al* 2007), climate change (Tylianakis *et al* 2008), pollution (Paoletti *et al* 2010), and the introduction of alien species (Vilà *et al* 2010), all of which interact with each other (Oliver and Morecroft 2014). Natural resources are exploited in social-ecological systems, where human societies are imbedded in natural ecosystems (Colding and Barthel 2019). For humans and ecosystems to interact in harmony, the rate of exploitation of natural resources should not exceed its growth rate and should not degrade ecosystems so severely that they cannot recover (Ostrom *et al* 1999). Unfortunately the amount of resources humans derive from nature increases rapidly due to population growth and increased wealth (Venter *et al* 2016), putting the balance between natural resources provisioning and exploitation at risk (Wackernagel *et al* 2021). To assure the continued prospering of both nature and humans, it is vital to restore this balance (Lampert 2019). To do so, a comprehensive understanding is needed of the dynamic interactions between natural resources provisioning and exploitation over space and time, as well as the different ways in which sustainable use of natural resources can be fostered, without duping those livelihoods depending on them (Partelow 2018). Researchers around the world are currently exploring ecosystems, societies and their dynamic relationships from various angles providing disciplinary, interdisciplinary and transdisciplinary knowledge (Preiser *et al* 2018).

One product that can jeopardize natural resources, yet has the potential to induce carbon neutrality, is biomass-based renewable energy, which includes fuels from crops (e.g., sugarcane), crop residue (e.g., rice straw) and wood (e.g., wood pellets) (Popp *et al* 2021). As global energy demands are expected to increase 28% by 2040 (Osman *et al* 2021), there is a need to invest in biomass-based renewable energy sources, to assure that they are produced in a carbon neutral way, and that their production does not impede food production and biodiversity (Fargione *et al* 2010, Popp *et al* 2021). Biomass-based renewable energy produced from wood (i.e., woodfuels) currently supplies about 9% of global primary energy and is responsible for approximately 55% of global wood harvest (Bailis *et al* 2015). The production of woodfuels can impede public health (Ezzati *et al* 2004), cause carbon emissions (Bailis *et al* 2015), as well as deforestation and forest degradation (Bailis *et al* 2005). Yet, woodfuels provide important household energy resources for nearly 2.6 billion people (Guta *et al* 2022), in particular in Sub-Saharan Africa (Smith *et al* 2019), and their production contributes greatly to economies (Zulu and Richardson 2013). If produced without decreasing or degrading forests, woofuels have the potential to be carbon neutral or even carbon positive (Liu *et al* 2022). Despite this opportunity, many countries push towards a transition from woodfuel to alternative energy resources and often marginalize interventions that aim for sustainable woodfeul production that promotes forest growth and sustains livelihoods (Doggart and Meshack 2017, Mwampamba *et al* 2013). Energy transitions to alternative energy sources, such as gas, will take time and resources, as they typically take more than 100 years to complete (Fouquet 2010), especially under a predicted 40% increase in demand for biomass-based energy across the African continent by 2040 (Smith *et al* 2019). In case of transitions to fossil fuels, energy transitions may not reduce carbon emissions and climate-change induced biodiversity losses on the long term (Harfoot *et al* 2018, Höök and Tang 2013). Such transitions may also trigger loss of income from those livelihoods producing and trading woodfuels (Smith *et al* 2019), and could potentially enhance the dependency of tropical nations on energy sources from elsewhere, as observed in India (Pode 2010) and Thailand (Nakawiro and Bhattacharyya 2007). Hence, it is important to identify ways in which biomass-based renewable energies can be produced sustainably by mitigating forest degradation and deforestation, while continuing to provide energy to billions of people around the world (Lattimore *et al* 2009). In this thesis, I explore effects of transitions that aim to induce sustainable forest use and livelihoods in one particular social ecological energy system: the charcoal production system.

## 1.1 The charcoal production system

In charcoal production systems, woody biomass (e.g., from trees and shrubs) is converted by charcoal producers into charcoal through carbonization. This process is governed through laws, rules and regulations on forest use and conservation, which are developed, implemented and enforced by a range of governing bodies (e.g., national, regional and local governments and third parties, such as NGOs) (van 't Veen *et al* 2022). Currently, charcoal production provides cooking-fuel for hundreds of millions of people, primary or secondary income for over 40 million people (FAO 2017), and vital energy for industry (e.g., the pig iron industry in Brazil) (Morello 2015). Charcoal production systems in the tropics exhibit a variation of input, conversion techniques and output (FAO 2017). Carbonization of wood into charcoal takes place in ovens, called kilns, which are either build on the spot from natural materials available at the harvesting site (e.g., earth mouth kiln), or made of durable materials, such as clay, and reused (e.g., beehive kiln) (FAO 2017). Charcoal producers derive woody biomass from forests (e.g., miombo woodlands or tropical rainforests) (Kalaba *et al* 2013, Sedano *et al* 2016) or forest plantations (e.g., Eucalyptus plantations) (Piketty *et al* 2009), each with their own specific biodiversity and functioning (Guo *et al* 2002, Sangeda and Maleko 2018). The conversion of woody biomass into charcoal currently results in up to 7% of deforestation globally (Chidumayo and Gumbo 2013), and is an important cause of forest degradation, which affects ecosystems services (Ahrends *et al* 2010), including biodiversity (Kouami *et al* 2009), and leads to carbon emissions (Sonter *et al* 2015). Charcoal-related carbon emissions are estimated at 71.2 million tons for $CO_2$ and 1.3 million tons for $CH_4$ (Chidumayo and Gumbo 2013), contributing significantly to global warming (Pennise *et al* 2001). Conversion rates from wood to charcoal in kilns range between 37% and 69%, indicating that the majority of carbon emissions from charcoal production result from the carbonization process and not the use of charcoal as an energy source (Pennise *et al* 2001).

Because a 5% increase in charcoal production is predicted by the year 2100 (Santos *et al* 2017), charcoal-related deforestation and carbon emissions are expected to rise in the future (Hillring 2006, Santos *et al* 2017). The impact of charcoal production on forests varies geographically, depending on demand and forest biomass availability, which is influenced by population size and urbanization (Nyembe 2011, Santos *et al* 2017). At a regional spatial scale, waves of demand may occur, spreading from centers of demand, such as cities or industry, outwards as a result of forest biomass depletion (Ahrends *et al* 2010, Zorrilla-Miras *et al* 2018). This causes a continuous shift of charcoal production to areas further away from centers of demand (Ahrends *et al* 2010, Zorrilla-Miras *et al* 2018). At local spatial scale, charcoal producers often harvest forests close to roads and residential areas first (e.g., close to village centers) and move further away from these areas once forest resources have been depleted, causing small waves of charcoal production from these residential areas and roads outwards (Baumert *et al* 2016, Ko *et al* 2011, Sedano *et al* 2016). Besides this, local scale charcoal production is influenced by (adherence to) laws, rules and regulations and the (presence of a) harvesting plan, which specifies the way in which charcoal should be produced (Syampungani *et al* 2017).

The carbonization process from woody biomass to charcoal is mainly carried out by rural producers, who, in most cases, sell charcoal to other users higher up the value chain, such as transporters and/or wholesalers to obtain income to sustain their livelihoods (Agyei, Hansen, and Acheampong 2018; Chiteculo et al. 2018). Transporters and wholesalers distribute the charcoal further to retailers and/or consumers (Baumert *et al* 2016, Vollmer *et al* 2017). Charcoal production is an important livelihood diversification strategy for rural producers (Jones, Ryan, and Fisher 2016). It enhances the sustainability of charcoal producer livelihoods (Smith *et al* 2017) because it provides access to additional income that is often invested in health care and education (Schaafsma *et al* 2014, Schure *et al* 2014). Producers rely on social networks and relations, allowing them to collaborate in charcoal production activities, to share knowledge and to sell charcoal (Agyei, Hansen, and Acheampong 2018; Baumert et al. 2016). Charcoal-related deforestation and forest degradation may limit the access charcoal producers have to woody biomass resources (Baumert *et al* 2016, Woollen *et al* 2016), which can jeopardize their income, education and health care (Brouwer and Magane 1999, Schaafsma *et al* 2014, Woollen *et al* 2016). Hence, charcoal-related forest degradation and deforestation may ultimately result in unsustainable charcoal producer livelihoods, potentially causing them to enter the poverty trap (i.e., a situation where charcoal producers experience a consequent loss of benefits, which cannot be offset by an increase in income, causing them to remain in the same financial position) (Schure *et al* 2014). This happens because charcoal production provides important livelihood diversification opportunities and secondary income that enhances resistance of producers to impoverishment (Vollmer *et al* 2017). Yet, charcoal production does not alleviate poverty and the majority of charcoal producers find themselves below the poverty line (Vollmer *et al* 2017). This is, in particular, related to unequal division of income from charcoal production along the charcoal value chain, where transporters and wholesalers receive the gross of the benefits (Agyei, Hansen, and Acheampong 2018; Baumert et al. 2016; Shively et al. 2010). Besides this, charcoal production may impede respiratory and physical health related to fumes from charcoal kilns and dust from charcoal collection (Kato *et al* 2004, de Souza *et al* 2020), as well as induce risks of injuries related to falling trees and heath combustion from kilns (Tiamiyu *et al* 2021).

At present, charcoal production is often governed through formal laws and formal or informal rules and regulations on forest use and protection, with the aim to mitigate (charcoal-related) forest degradation and deforestation and/or promote sustainable livelihoods (Schure *et al* 2013, van 't Veen *et al* 2022). These laws, rules and regulations differ between geographical regions, such as villages, districts and countries, and may include formal laws, rules and regulations (e.g., those described in a forest act), and informal rules and regulations (e.g., societal norms) (van 't Veen *et al* 2022). The existing formal and informal rules and regulations may or may not be adhered to by those operating in charcoal production systems (Brobbey *et al* 2015, Schure *et al* 2013). In many tropical regions, illegal charcoal production takes place, defined as production that is not in accordance to formal laws, rules and regulations, e.g., in Kenya (Iiyama *et al* 2017, Ruuska 2013, Sola *et al* 2021), Brazil (Brito and Barreto 2011, Glaser *et al* 2003, Otsuki 2012), Nigeria (Agunloye *et al* 2020, Ekhuemelo *et al* 2017, Meduna *et al* 2009) and Tanzania (Butz 2013, Sander *et al* 2013, Schaafsma *et al* 2012), Malawi (Smith *et al* 2015, 2017, Zulu 2010). At present, the extent to which illegal charcoal production occurs remains unknown at global scale (Schure *et al* 2013). Yet, uncontrolled production has been linked to forest degradation and deforestation (Bolognesi *et al* 2015, Dons *et al* 2015), and could cause overexploitation of forest resources, in particular at high charcoal demands (van 't Veen *et al* 2021). Various (new) laws, rules, regulations and policy interventions are implemented to reduce the negative impacts of charcoal production on forest resources and biodiversity, as well as to sustain charcoal producer livelihoods (FAO 2017). This results in a set of charcoal production systems around the world, each with their own specific social, economic and political setting, governance system, carbonization techniques, and woody biomass sources from which charcoal is produced (van 't Veen *et al* 2021).

Several interventions exist that promote a transition towards more sustainable charcoal production systems (FAO 2017). Interventions are applied at different stages of the charcoal production cycle, either as a standalone intervention, in parallel to other interventions and/or in combination with other interventions (FAO 2017). Interventions can be grouped in those interventions that: (i) provide an external input to the livelihood assets of charcoal producers to increase the efficiency of charcoal production (Bailis 2009), (ii) initiate a transition in charcoal production systems to reduce deforestation and forest degradation (Lejeune *et al* 2013, Ishengoma *et al* 2016), and (iii) decrease demand by promoting sustainable consumption and the use of alternative energy sources (Broto *et al* 2018, Kojima 2011). Interventions to increase production efficiency include the introduction of efficient charcoal production kilns, which have a higher conversion rate of wood to charcoal (Bailis 2009, Bailis *et al* 2013). These interventions aim at reducing the extent of forest cut to derive a certain amount of charcoal to decrease charcoal-related carbon emissions (Mwampamba *et al* 2013). Interventions that transform charcoal systems include charcoal bans (e.g. Kenya, Dominican Republic, Gambia and Eritrea) and permit systems (e.g. Tanzania, Ghana and Indonesia) but also the introduction of forest plantations, community-based natural resources management (FAO 2017), and self-organization of charcoal production on communal village ground (e.g. in Indonesia and Malawi) (Chingaipe *et al* 2015, Prasetiamartati *et al* 2008). Interventions that reduce charcoal demand mainly involve the promotion of alternative fuels, such as gas and renewables (Broto *et al* 2018, Kojima 2011), as well as the introduction of sustainable cooking stoves through subsidies (Dagnachew *et al* 2020, Mwampamba *et al* 2013). However, at the moment, effects of specific interventions on forests and livelihoods often remain unclear, which exposes an important knowledge gap that needs to be addressed in order to foster sustainability in charcoal production systems (Mwampamba *et al* 2013). Specifically, there is a need to explore long-term effects of interventions on forests and charcoal producer livelihoods to allow for the mitigation of charcoal-related forest degradation, deforestation and carbon emissions, without reducing the livelihood benefits charcoal producers derive from their production practices.

To fully understand long-term effects of interventions aiming for sustainability in charcoal production systems, it is important to take social, economic and political settings into account, as they may affect the suitability and success of these interventions (FAO 2017). In some countries, such as Tanzania and Uganda, charcoal production is strongly influenced by political agendas that aim to control charcoal-related deforestation and/or minimize illegal production to avoid tax evasion (Branch and Martiniello 2018, Sander *et al* 2013). Social, economic and political settings affect charcoal demands (Faye 2017, Faye and Ribot 2017) and the governance in place (Schure *et al* 2013), which influences the amount of charcoal that is produced (FAO 2017) and, consequently, charcoal-related deforestation, forest degradation (Kamwilu *et al* 2021) and carbon emissions (Sonter *et al* 2015). For example, population increase in Ghana has significantly enhanced energy demands, including demands for charcoal (Anang *et al* 2011). On its turn, deforestation may influence the political setting of countries (Burgess *et al* 2012), which can result in an adjustment of the governance to control charcoal production (Branch and Martiniello 2018, Faye 2017). For instance, high demands for charcoal, resulting from population growth and enhanced human wellbeing, recently caused a rise of charcoal production in Kenya, leading to a depletion of national forest stocks, to which the government responded with strict laws that ban production (Kamwilu *et al* 2021).

## 1.2 Defining charcoal systems as social-ecological systems

The charcoal production system is well aligned to be conceptualized as a social-ecological system because it has provides humans with a product derived through exploitation of natural resources. Social-ecological systems are defined as two interacting sub-systems, (i) the ecological sub-system, also referred to as the ecosystem and (ii) the social sub-system, which includes the economic and social conditions of life in a human society (Colding and Barthel 2019). The charcoal system can be operationalized by assessing its social-ecological components and their complex interactions with one another. Through this lens, social-ecological system theory can help propose hypotheses on social-ecological system dynamics and organize and interpret findings.

### *1.2.1 Social-ecological systems*

Social-ecological systems theory sheds light on the ways in which humans and nature interact over space and time and identifies ways to restore balance between them, hereby emphasizing that humans are a part of nature (Colding and Barthel 2019). The ecological sub-system of social-ecological systems include ecosystems, such as a tropical dry forests that cover specific geographical areas around the globe and produce natural resources, such as wood (Freudenberger *et al* 2012, Olson *et al* 2001). Ecosystems have evolved over millions of years, changing constantly with regard to their geo-physical environment (Azaele *et al* 2006). Hence, ecosystems are composed of a unique set of species, which interact with each other (Chamberlain *et al* 2014, Tylianakis *et al* 2008). On their turn, societies also evolved over thousands of years (Moffett 2013), exploiting natural resources to sustain themselves (Eppinga *et al* 2021). The interaction between humans and nature has been ruled by governance, i.e. laws, rules and regulations to govern and manage ecosystems and the resources they provide (Agrawal *et al* 2008, Arts *et al* 2010). In social-ecological systems, it is therefore assumed that societies govern their interactions with ecosystems and, therefore, can alter the balance between humans and nature (Walker *et al* 2004, 2002).

### *1.2.2 A multitude of frameworks for analyzing social-ecological systems*

Due to the dynamic nature of social-ecological systems and the multitude of interacting societal and ecological variables within them, a wide range of researchers from a variety of disciplines have proposed frameworks to conceptualize social-ecological systems and their interactions (Binder *et al* 2013). Ten social-ecological system frameworks are widely used by scientists and practitioners (Binder *et al* 2013). These frameworks can be organized around three main criteria (Binder *et al* 2013). The first criterion is uni- or bidirectional conceptualization of interactions between social and ecological systems, which indicates whether interaction between social and ecological components are mainly explored in one direction (e.g., from ecosystems to society) or whether frameworks acknowledge feedbacks between social and ecological components (Binder *et al* 2013). The second criterion is the framing of social-ecological system frameworks from an anthropogenic or an ecocentric perspective, which indicates whether the framework mainly emphasizes implications of social-ecological system dynamics on society or ecosystems (Binder *et al* 2013). The third criterion is framing of social-ecological system frameworks from an analysis-oriented or an action-oriented perspective, indicating whether the framework is meant to guide scientific endeavors or whether it is meant to guide practitioners in designing and implementing policies aimed at achieving sustainability in social-ecological systems.

## 1.3 Ostrom's social-ecological systems framework

One of the most famous publications on social-ecological systems theory originates from Elinor Ostrom, who proposed a specific conceptualization of social-ecological systems and the interactions between the different components (Ostrom 2007). In this thesis, I used the social-ecological systems framework of Elinor Ostrom (Ostrom 2009) to identify research gaps, guide my research, and organize my findings. The social-ecological systems framework is bidirectionally conceptualized from an anthropogenic perspective and is analysis-oriented (Ostrom 2009). Its bidirectional nature allowed me to explore effects of transitions in charcoal production systems on both forests and livelihoods and understand their interactions. Its analysis-oriented nature allowed me to use the framework as a guide to formulate research questions and organize findings on various social and ecological components of charcoal production systems.

### *1.3.1 Adaptation of Ostrom's social-ecological systems framework to the charcoal system*

**Figure 1.1** shows the adaptation of Ostrom's framework and its components for the charcoal production system. According to Ostrom's vision, social-ecological systems consist of resource units, which are natural resources harvested from specific ecosystems, such as tropical dry forests or plantations in the case of charcoal production systems (Ostrom 2007, 2009). The resource units are found within a resource system, defined as an area of resource units within a specified boundary, such as a forest conservation area (Ostrom 2007, 2009) or in the case of charcoal production systems, a forest area in a village, district or country (Doggart 2016). Resource systems exist at different nested scales, ranging from global to national, regional, local and individual (i.e., private properties) (Cumming *et al* 2006). For example, resource systems at national levels are forest areas in countries (e.g., Tanzania) in charcoal production systems, at regional level they may be forest areas in districts (e.g., the district of Kilosa in Tanzania), while at local level they may forest areas in villages (e.g., the village Kigunga in Tanzania). Previous research has studied aspects of charcoal production systems in a large range of resource systems, from forests in villages (Akoa *et al* 2007a), to districts (Sedano *et al* 2016), to countries, to groups of countries or continents (Falcao 2008, Zulu and Richardson 2013), and the entire world (Chidumayo and Gumbo 2013). The resource system is governed by a governance system that introduces laws, rules and regulations under which users, such as charcoal producers, operate (Ostrom 2007, 2009). The resource system is exposed to specific social, economic, and political settings, which include demand for charcoal (Zulu 2010), political stance on charcoal production (Sander *et al* 2013), and the socio-economic status of charcoal producers operating in the resource system (Vollmer *et al* 2017).

Social-ecological system components interact with each other over space and time (Ostrom 2007, 2009), e.g., users exploit natural resources under the guidance of governance systems, which on their turn are adjusted based on the behavior of users and the available stock of resource units. Interactions between different social-ecological system components produce outcomes, i.e., the state of the different components and its related ecosystem at a specific point and place in time (Ostrom 2007, 2009). For example, interactions between demand and charcoal producers may result in exploitation of forests, causing forest degradation or deforestation (Ahrends *et al* 2010). Additionally, the provisioning of subsidies for charcoal production from agroforestry by governments, in combination with rules and regulations that limit extraction of natural forest resources, may enhance income producers receive from charcoal production, as well as reduce forest degradation (Iiyama *et al* 2017). To understand dynamics of social-ecological systems, it is important to study spatiotemporal interactions between the different components closely and to assess impacts of changes in one of the components on the other components (Partelow 2015, 2018). For example, one may assess effects of land use, climate change, energy policies, user behavior and livelihood needs.

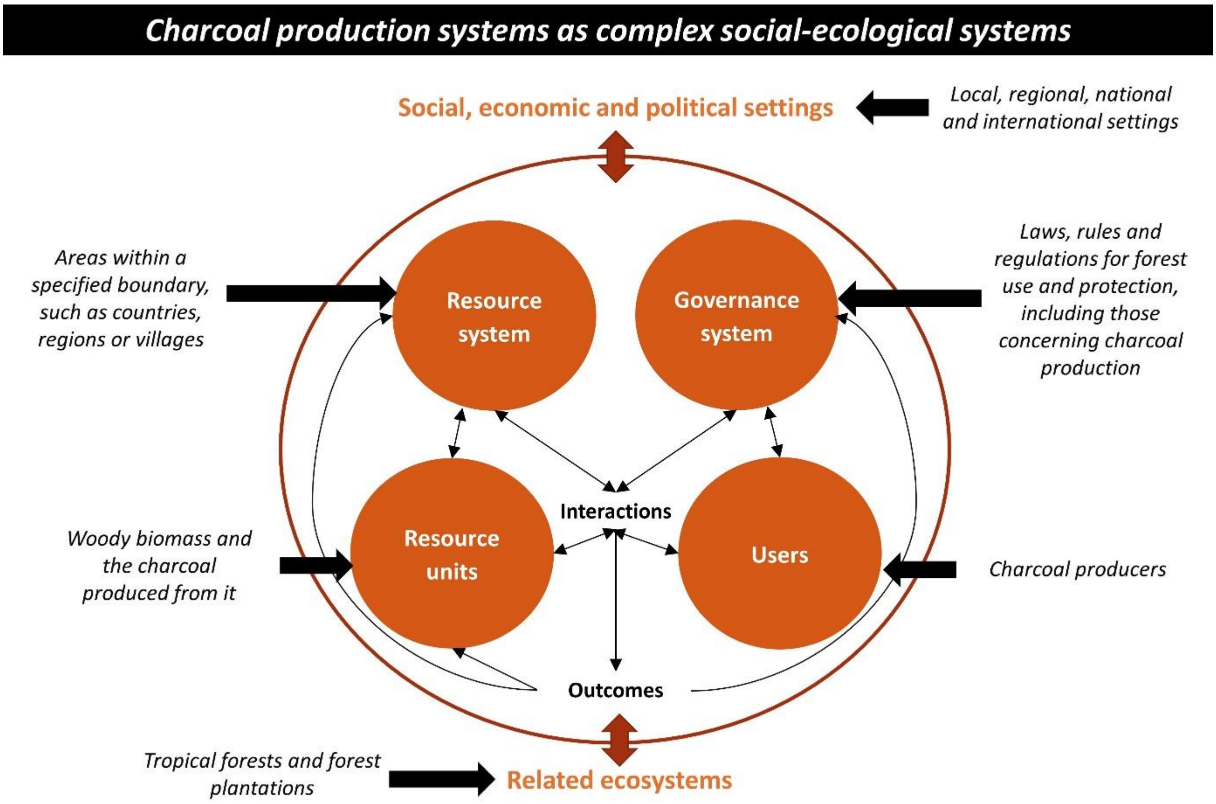


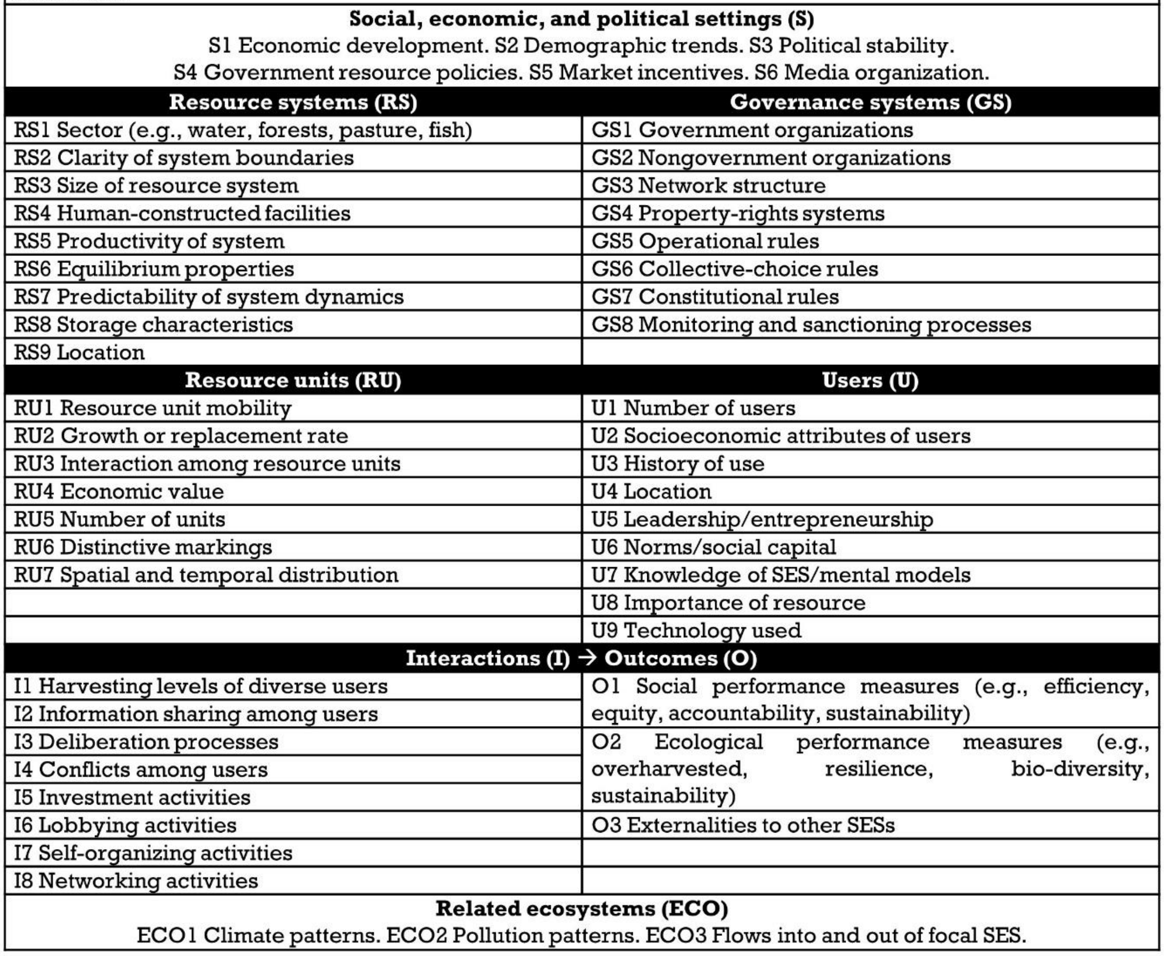
**Figure 1.1**. Introducing the charcoal production system as a social-ecological system using the social-ecological systems framework of Elinor Ostrom (Ostrom 2007, 2009), which illustrates the interactions between different components and the outcomes they produce.

According to Ostrom's framework, each component of the social-ecological systems is composed of secondary components that interact with each other (**Table 1**) (Ostrom 2009). For example, users in the systems do not only interact with natural resources but also interact with other users to exchange knowledge (Olopade *et al* 2019, Rolleston 2011), finances (Béné *et al* 2014) and to form social networks (Emery and Flora 2006, Plummer and FitzGibbon 2006). It is important to assess how these secondary components influence the broader social-ecological system (Asah 2008). For instance, analyzing interactions between sub-components enables us to understand the role of knowledge and social networks on the way charcoal producers (i.e., users) extract woody biomass resources (i.e., resource units) (Gibson, Williams, and Ostrom 1999), and respond to the governance system that specifies rules and regulations for (charcoal-related) forest use and extraction (Lajili 2015, Go *et al* 2013). Systematic tools and frameworks are necessary to dissect and harness complexity of relationships between different interacting components of the social-ecological system (Colding and Barthel 2019). In 2009, Elinor Ostrom proposed a way to operationalize social-ecological systems that can be used to identify relevant secondary components, i.e. variables to study in a specific social-ecological system in a particular spatiotemporal setting (Ostrom 2009). By studying the variables in a systematic way, results from multiple social-ecological system studies, such as studies on charcoal production systems, can be combined and analyzed together to gain a better understanding of the spatiotemporal dynamics and interactions in social-ecological systems around the world (Epstein *et al* 2020).

### *1.3.2 Critiques on the social-ecological systems framework*

Like any scientific theory, the social-ecological systems framework has been criticized following its introduction (Partelow 2018), and multiple alternative components (Epstein *et al* 2013), and frameworks (Mcginnis and Ostrom 2014) have been proposed to overcome its limitations. Critics of

**Table 1.1** The secondary components under the primary components of the social-ecological systems framework of Elinor Ostrom (Figure 1.1) (Ostrom 2009). This table is an exact copy of Table 1 in Elinor Ostrom's article on "A General Framework for Analyzing Sustainability of Social-Ecological Systems" of 2009 in Science.



| | |
|---|---|
| **Social, economic, and political settings (S)**<br>S1 Economic development. S2 Demographic trends. S3 Political stability.<br>S4 Government resource policies. S5 Market incentives. S6 Media organization. | |
| **Resource systems (RS)** | **Governance systems (GS)** |
| RS1 Sector (e.g., water, forests, pasture, fish) | GS1 Government organizations |
| RS2 Clarity of system boundaries | GS2 Nongovernment organizations |
| RS3 Size of resource system | GS3 Network structure |
| RS4 Human-constructed facilities | GS4 Property-rights systems |
| RS5 Productivity of system | GS5 Operational rules |
| RS6 Equilibrium properties | GS6 Collective-choice rules |
| RS7 Predictability of system dynamics | GS7 Constitutional rules |
| RS8 Storage characteristics | GS8 Monitoring and sanctioning processes |
| RS9 Location | |
| **Resource units (RU)** | **Users (U)** |
| RU1 Resource unit mobility | U1 Number of users |
| RU2 Growth or replacement rate | U2 Socioeconomic attributes of users |
| RU3 Interaction among resource units | U3 History of use |
| RU4 Economic value | U4 Location |
| RU5 Number of units | U5 Leadership/entrepreneurship |
| RU6 Distinctive markings | U6 Norms/social capital |
| RU7 Spatial and temporal distribution | U7 Knowledge of SES/mental models |
| | U8 Importance of resource |
| | U9 Technology used |
| **Interactions (I) → Outcomes (O)** | |
| I1 Harvesting levels of diverse users | O1 Social performance measures (e.g., efficiency, equity, accountability, sustainability) |
| I2 Information sharing among users | |
| I3 Deliberation processes | O2 Ecological performance measures (e.g., overharvested, resilience, bio-diversity, sustainability) |
| I4 Conflicts among users | |
| I5 Investment activities | |
| I6 Lobbying activities | O3 Externalities to other SESs |
| I7 Self-organizing activities | |
| I8 Networking activities | |
| **Related ecosystems (ECO)**<br>ECO1 Climate patterns. ECO2 Pollution patterns. ECO3 Flows into and out of focal SES. | |

the social-ecological systems framework argue that definitions of social-ecological systems vary and are often not provided (Colding and Barthel 2019). Colding et al. (2019) found that 61% of the publications up to 2017 does not provide a definition of social-ecological systems, challenging comparability between studies and the usefulness of the social-ecological systems framework. Additionally, Epstein et al. (2013) highlighted a lack of emphasis on ecological aspects in the social-ecological systems framework. To overcome this, an additional primary component to the social-ecological systems framework could be introduced, namely ecological rules, which may provide a more nuanced overview of outcomes (Epstein *et al* 2013). Besides this, methodological challenges arise when applying the social-ecological systems framework of Elinor Ostrom (Partelow 2018), in particular with regard to understanding the interactions between the different components (Partelow 2015). Partelow (2018) identified four main methodological gaps that may explain issues in the application of the social-ecological systems framework. First, the variables in the social-ecological systems framework are often not well defined and may be interpreted differently depending on the context in which they are addressed (i.e., the variable-definition gap) (Partelow 2018). Second, the conversion of a variable to a measurable and comparable indicator remains challenging, where in the end different indicators may be chosen to measure a specific variable depending on the context and type of social-ecological system (i.e., the variable-to-indicator gap) (Partelow 2018). Third, even when the variable definitions and indicators align, the way indicators are measured may still deviate between two studies, challenging their comparability (i.e., the indicator-measurement gap) (Partelow 2018). Finally, raw data for different indicators of social-ecological systems is often transformed to different structures to present and compare it, which alters interpretations of those who study the final results (i.e., the data transformation gap) (Partelow 2018).

### *1.3.3 Considering critiques on the social-ecological systems framework*

Despite his critiques, Partelow (2018) argues that the strength of the social-ecological systems framework lies in its flexibility and its multi-purpose applicability, as long as methodological transparency is pursued. Changes to the original framework are, furthermore, welcomed to adjust the framework to policy settings (Partelow 2018). Both additional theory and empirical results will continue to provide a more holistic and comprehensive framework and understanding of social-ecological systems in the future (Mcginnis and Ostrom 2014). Throughout my PhD thesis, I position all Chapters within the original social-ecological systems framework of Elinor Ostrom (**Figure 1.1**) (Ostrom 2007, 2009), which defines the social-ecological system. I do not use the social-ecological systems framework as a methodology but rather as an organizational tool to (i) identify research gaps and (ii) organize research outcomes. This fits the analysis-oriented nature of the framework. The framework functions as a reminder that a change in a specific component of a social-ecological system (e.g., the governance system), causes a chain of complex dynamic interactions between all components, ultimately changing the outcome of the social-ecological system. Hence, I use the social-ecological framework of Elinor Ostrom as a tool to conceive order in the complexity that result from conducting interdisciplinary research on both social and ecological processes, while combining results from a large variety of methods covering varying spatiotemporal scales. The flexibility and multi-purpose applicability of the original social-ecological systems framework supports this purpose. While this PhD thesis does not aim to advance social-ecological systems theory, the research conducted highlights ways in which different types of data, methods and indicators may be combined to understand (interactions between) social-ecological systems components. Hereby, it sheds light on the ways in which the four main methodological gaps Partelow (2018) identified could be addressed in the future and whether additional primary and/or secondary social-ecological system components, such as ecological rules (Epstein *et al* 2013), could advance the social-ecological systems framework. For example, I address methodological challenges in the discussion of each Chapter of this thesis. Overall, careful attention is paid to assure that variables assessed in this thesis translate to measurable and aligned indicators that can be collected with data in a systematic, robust and scientifically defensible way. Finally, by defining all variables and indicators used in this thesis, I aim to pursue methodological transparency. Through this approach I hope that other scientists may use the outcomes of this research for comparison, allowing me to ultimately contribute to an enhanced understanding of social-ecological systems as a whole, despite the focus on one specific social-ecological system.

## 1.4 Principles of managing charcoal commons sustainably

Most charcoal is produced in forests that are commons, meaning that it is produced from a type of natural resource of which the characteristics and mere size challenge the exclusion of users who benefit from the resources (will be referred to as commons hereafter) (Ostrom 2000). Elinor Ostrom identified eight design principles that can foster sustainable management of common pool resources in a social-ecological system (Mcginnis and Ostrom 1992, Stern 2011). According to Ostrom's theory, sustainability of commons in social-ecological systems, such as many charcoal production systems, relies on a set of principles (Mcginnis and Ostrom 1992). **Table 1.2** provides an overview of these principles, the rationale behind them, and their relevance for charcoal production systems. In the Synthesis of thesis, I assess whether the design principles of Ostrom are adhered to upon transitions in charcoal production systems and whether they are promoted by interactions between different social-ecological system components.

**Table 1.2** The eight design principles for managing common pool resources sustainably (Mcginnis and Ostrom 1992).

| Elinor Ostrom's design principles | Interpretation | Relevance for charcoal production systems |
|---|---|---|

| | | |
|---|---|---|
| **Define boundaries for user groups** | Boundaries provide clarity on who can use the resources and where they can be produced | Forests often lack natural boundaries, spanning wide areas that cover different villages and land under various rules and regulations for tenure (Yadav *et al* 2003). Clear boundaries are necessary to assure that producers are aware of the areas where charcoal production is allowed and who may produce it to prevent conflicts (Jagger 2014). |
| **Devise rules congruent with local social-ecological conditions** | Rules and regulations for natural resource use should be crafted by local people, who are aware of the ecological rules of the natural resources used in their community. | In many regions of the tropics, in particular sub-Saharan Africa, charcoal is produced on land tended for by local communities, under specific social-ecological circumstances (Doggart 2016, van 't Veen *et al* 2022). Members of local communities, such as members of the local government, should be involved in the creation of laws, rules and regulations for forest use to assure that they fit the local conditions that might not be so evident to policy makers from outside the communities (Grouwels *et al* 2021, Kamwilu *et al* 2021). |
| **Allow most users to participate in decision-making regarding the use of the natural resource** | Inclusion of users in developing rules for the use of assures their awareness of them, may improve their fit to local circumstances, and may motivate users to adhere to them. | To assure the congruence between rules and regulations for charcoal production and local social-ecological conditions, it is vital that local charcoal producers are involved in decision making regarding these rules and regulations (Grouwels *et al* 2021, Kamwilu *et al* 2021). |
| **Commons must be monitored** | Communities managing commons should monitor whether the use of natural resources complies with the laws, rules and regulations set to assure sustainable management is practiced. | The majority of charcoal producers operate in forest commons, which cover vast areas within their communities (FAO 2017). Charcoal production can easily go undetected in such large spaces, which causes illegal production, indicating a need to monitor forests regularly, e.g., through patrols, to assure all producers oblige to the laws, rules and regulations in place (Schure *et al* 2013). |
| **Apply graduated sanctions** | Graduated sanctions are those that build up gradually, so that the offender is not immediately banned from using the commons but first receives a range of (informal) warnings to prevent resentment of users towards those who monitor commons. | As described in Section 1.1, illegal charcoal production is widespread in the tropics (Bolognesi *et al* 2015); yet it provides an important livelihood income for producers (Khundi *et al* 2011), many of whom are poor (Vollmer *et al* 2017). Often confusion exists about implemented laws, rules and regulations for charcoal production (Mugo and Ong 2006). Therefore, it is important to assure that charcoal producers receive multiple chances to oblige the laws in place. |
| **Develop low-cost conflict resolution mechanisms** | All users should have access to mechanisms that enable them to resolve conflicts regarding their commons, to assure that problems are solved and not ignored in the community. | Conflicts may occur between charcoal producers and between charcoal producers and other villagers because of land tenure rights (e.g., charcoal production occurs on the land of another villagers), illegal production that degrades forests, and different land uses (e.g., livestock grazing in forests) (Butz 2013, Kanton 2019, Mapesa *et al* 2013). To solve these conflicts, it is vital that charcoal producers have access to low-cost conflict resolution mechanisms (Kamwilu *et al* 2021). |

| | | |
|---|---|---|
| **Assure that commons are nested in larger networks** | Commons should be nested in larger networks that allow for cooperation beyond local communities, as commons within a specific community also span those of neighboring communities and the laws, rules and regulations of commons use should fit within those of the wide region and nation. | General laws, rules and regulation of forest use often exist at national scale in tropical countries (van 't Veen *et al* 2022). These are designed, implemented and/or monitored by a range of institutes, such as local governments, district governments and/or national governing bodies (e.g., a ministry of natural resources), each with their own (overlapping) tasks (van 't Veen *et al* 2022). It is important that knowledge exchange occurs between these different governing bodies, to make sure that everyone is aware of the laws, rules and regulations in place at different scales, and to make sure that local laws, rules and regulations crafted by communities fit within the wider scope of the nation's forest governance system. |

## 1.5 Gaps in knowledge

### *1.5.1 Gaps in knowledge in charcoal production systems*

Despite its importance as a global energy and income source, charcoal is arguably among the least studied forest products. Although the importance of charcoal production for livelihood diversification of charcoal producers has been emphasized (Jones et al. 2016; Smith, Hudson, and Schreckenberg 2017), research focused mainly on the role of charcoal for income generation and the way it is invested in education and health care (Schure *et al* 2014). It has been observed that charcoal production is often an activity carried out by the poor, who upon enhancing their income move away from charcoal production to alternative activities (Vollmer *et al* 2017, Zulu and Richardson 2013). Rural livelihoods, however, likely rely on access to other aspects beyond income and education, such as knowledge about charcoal production and the forest, as well as social networks to share this knowledge, to name a few (Scoones 1998). Additionally, although charcoal is often mentioned as an important source of deforestation (Chidumayo and Gumbo 2013) and forest degradation (Dons *et al* 2015), the exact locations of charcoal production sites largely remain unknown. Charcoal production has been successfully detected and monitored in a handful of regions around the world (e.g., in the Tete province of Mozambique) (Sedano *et al* 2016, 2020a). Besides this, although many studies have shown a decrease in forest biomass and tree biodiversity upon charcoal production (Ryan *et al* 2014, Kalaba *et al* 2013), limited studies assess the effects of different social-economic and ecological drivers on the manner in which forest biomass and biodiversity is altered in charcoal production systems. For example, drivers behind the intensity of tree cutting for charcoal production and the size and distribution of charcoal production sites remain unclear, challenging the development of spatial models that predict charcoal production and its implications on forest ecosystems. Hence, important research gaps remain on specific primary and secondary components of charcoal production systems and, particularly, on their interactions.

Further, there is a lack of concencus on whether existing strategies aiming for sustainability transitions in charcoal production systems achieve their social and environmental objectives (Mwampamba *et al* 2013). For example, although permit systems have been implemented in most charcoal producing countries, illegal charcoal production occurs due to limitations in enforcing laws, rules and regulations for forest use and conservation (Schure *et al* 2013). Additionally, the impact of governance interventions, such as bans and transitions to plantations or community-based natural resources management on forests and livelihoods often remains unclear (Mwampamba *et al* 2013). For example, governmental bans in Kenya shifted charcoal production to neighboring countries (e.g. Somalia), relocating pressures to forest elsewhere (UN 2016). Banning charcoal production locally could also induce energy shortages if charcoal supplies are reduced or halted, which could jeopardize livelihoods depending on charcoal to cook (Chauvin 1989). Plantations may provide an alternative wood source for charcoal producers (Pinto *et al* 2018) but may exclude producers that do not own land or do not have access to plantations. While most community-based natural resources management projects do not focus on charcoal production directly, those that do show an increase in forest cover and/or livelihood benefits (Doggart 2016, Ishengoma *et al* 2016, WB 2010b). Similarly, although the introduction of sustainable cooking stoves is likely to reduce consumption (Dagnachew *et al* 2020, Lejeune *et al* 2013), it is yet unknown whether this reduces charcoal production significantly or whether producers find alternative buyers for their charcoal (Mwampamba *et al* 2013). Effects of government subsidies for alternative energy resources on charcoal production are overall variable (Kojima 2011). Although many countries transitioned towards alternative fuels in the recent past (Geilfus 1997, Perez-Lopez 1981), this transition is difficult to achieve due to the strong consumer preference for charcoal, and the unreliable supply of alternative energy resources in low income countries (Kojima 2011). Finally, it is important to assess whether transitioned charcoal production systems relying on commons adhere to design principles for sustainable commons management.

### *1.5.2 Gaps in knowledge in social-ecological systems*

Although much attention has been paid to social-ecological systems theory and practice over the last decades (Binder *et al* 2013), many research gaps remain (Herrero-Jáuregui *et al* 2018). Many studies focus on several elements of social-ecological systems through studies on resilience, sustainability, governance or ecosystem services (Herrero-Jáuregui *et al* 2018), while limited studies focus on social-ecological systems as a whole (Herrero-Jáuregui *et al* 2018), failing to consider all components and their interactions. In particular, feedbacks between social and ecological variables remain understudied (Herrero-Jáuregui *et al* 2018). Additionally, relatively more attention is paid to the societal than the ecological components of the social-ecological systems (Epstein *et al* 2013). Based on a literature review, Herrero-Jáuregui et al. (2018) argued that social-ecological systems theory and frameworks are still under construction. These authors recommend a transdisciplinary approach to social-ecological systems science in which biophysical scientists work with social scientists to integrate social and ecological data (Herrero-Jáuregui *et al* 2018). These authors, furthermore, agree with Epstein et al. (2013) that an enhanced focus on ecology is needed, highlighting the importance of gathering biophysical data, to better understand ecosystem service delivery in social-ecological systems (Herrero-Jáuregui *et al* 2018). Besides this, the authors recommend the development of methodological tools that can integrate social and environmental data to study feedbacks between ecosystems and society (Herrero-Jáuregui *et al* 2018). Finally, there remains a need to understand transitions in social-ecological systems (Milkoreit *et al* 2018), in particular on ways in which a stable dynamic relationship between social and ecological system components can be achieved under varying levels of demand for products and services from nature (Pereira *et al* 2018, Vermunt *et al* 2020).

## 1.6 Research questions and hypotheses

In this thesis, I explored different social and ecological components of charcoal production systems in the tropics, their interactions and their response to interventions that aim to initiate sustainability transitions, in particular transitions in governance. I focused on charcoal production in the tropics because most charcoal is produced in this region (FAO 2017), a large amount of users relies on charcoal for their livelihoods (Zulu and Richardson 2013), the impact of charcoal production on forests and their ecosystem services mainly occurs in this region (Chidumayo and Gumbo 2013), and demand is likely to grow in the future (Santos *et al* 2017). I aimed to fill some of the previously identified knowledge gaps on social-ecological system components and dynamics to understand impacts of transitions in charcoal production systems on forest use and the livelihoods of charcoal producers in the tropics. The overarching research question was:

*What is the impact of transitions in charcoal production systems on forest use and charcoal producer livelihoods?*

The main expectation is that charcoal production systems can enhance both forest and livelihood sustainability, under the assumption that enough knowledge is available on system component interactions that can be triggered to resolve pressures guided by demand, climate change and livelihood development. To fulfill the aim of this thesis, I assessed different primary and secondary social-ecological system components of charcoal production systems and their (spatiotemporal) interactions. The main overarching research question of this PhD thesis served as a guide to formulate research questions for all chapters of this thesis. In order to provide an answer to the overarching research question, I divided the work in this thesis into three main research questions, which I answered in eight Chapters based on the conceptual framework of Elinor Ostrom:

1. *What is the spatiotemporal effect of transitions in charcoal production systems on forest use?*
2. *What is the effect of transitions in charcoal production systems on the livelihoods of charcoal producers?*
3. *What is the effect of forest governance on charcoal production and forests?*

**Figure 1.2** provides a conceptual framework of the different social-ecological trajectories I hypothesize as a result of transitions in charcoal production systems from a baseline perspective. First, I expect that transitions to low demand, alternative energies (e.g., gas) and effective governance enhance forest resource availability, because they reduce the need to convert forest resources into charcoal, because they regulate the extraction of forest resources, or because they replace the production of charcoal from forests by production from plantations. Besides this, I expect effective governance to promote livelihood sustainability of charcoal producers, defined as access of charcoal producers to all livelihood resources (i.e., livelihood capitals), including natural capital (i.e., forest resources), human capital (i.e., knowledge and health), financial capital (i.e., income and charcoal production), and physical capital (i.e., physical assets, such as housing). I, in particular, expect those

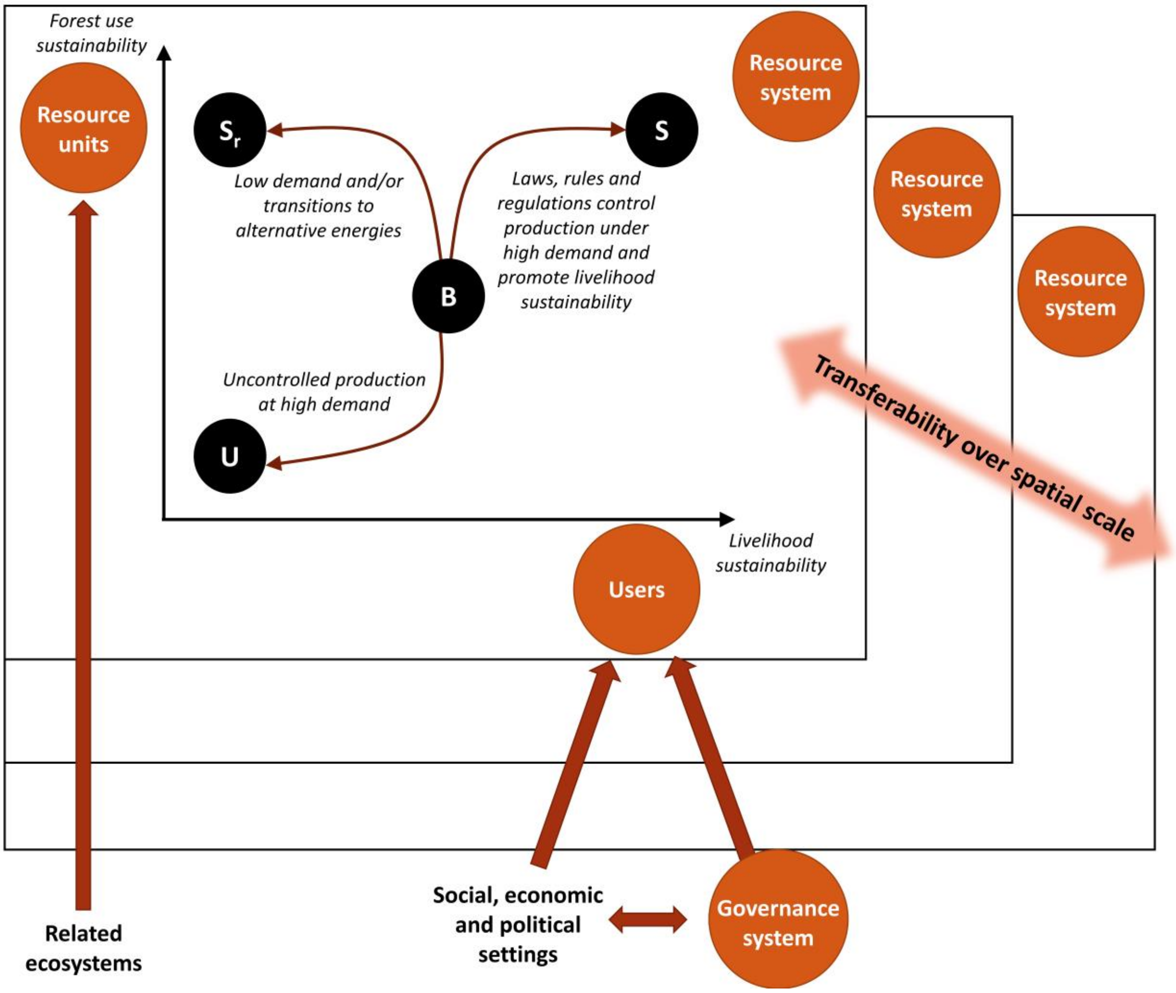


**Figure 1.2**. Conceptual framework visualizing interactions between the different primary social-ecological system components in charcoal production systems, where resource units are forest biomass resources, users are charcoal producers, resource systems are natural resources within a defined boundary (e.g., a forest within a village, district or nation), and governance systems are sets of formal laws and formal and informal rules and regulations about forest use and conservation that apply in a resource system. Related ecosystems are those forest ecosystems in which charcoal production takes place and social, economic and political settings are the social, economic and political setting that influence a resource system. The graph in the middle indicates the interaction between the resource unit and user components of charcoal production systems and the effect of transitions in charcoal production systems, which is the interaction that can readily be assessed when we theoretically or empirically combine data of resource units and users. In total, we tested three scenarios: (i) A reduction in demand and/or a transition to alternative energy sources, (ii) laws, rules and regulations aimed at controlling production and at enhancing charcoal producer livelihood sustainability at high demand, and (iii) uncontrolled production at high demands. We hypothesize that these scenarios result in three alternate states in charcoal production systems: (i) $S_r$: Sustainable use of forest resources at the expense of charcoal producer livelihood sustainability, (ii) S: Sustainable use of resources and sustainable livelihoods of charcoal producers, and (iii) U: Both unsustainable use of resources and livelihoods of charcoal producers.

governance transitions that foster communal management to result in sustainable livelihoods of charcoal producers, as they aim to meet Ostrom's design principles for sustainable management of commons that both mitigate degradation of natural resource stocks, such as forests, and enhance livelihood sustainability. Hereby, I hypothesize that charcoal producers adhere to the rules and regulations for charcoal production specified in communal management harvesting plans. In contrast, I expect unsustainable charcoal producer livelihoods upon interventions that transition charcoal production systems to low demand levels or alternative energies, as users lose an important primary or secondary source of income from charcoal production. Upon uncontrolled production under high levels of demand, I hypothesize a drop in available forest resources, which will ultimately jeopardize charcoal production activities, resulting in a loss of important income for charcoal producers. Finally, I expect that transitions in charcoal production systems observed at local scale do not directly transfer to national and international scale, as such local transitions often do not percolate to larger governance scales. Instead, I expect that charcoal production at national and international scale is mainly driven by countries' social-economic status, which determines the demand for charcoal as main energy source. This, because we expect that countries with high social-economic status have shifted to alternative energy sources, such as gas, while countries with lower social-economic status remain reliant on charcoal.

# Chapter 2

## Introduction to charcoal production systems in the tropics

Charcoal production is governed under multiple governance systems that operate under varying ecological and social-economic settings around the tropics (FAO 2017). Governance systems of charcoal production systems dictate laws, rules and regulations to reduce negative implications of charcoal production on forest resources and biodiversity (FAO 2017), as well as to sustain livelihoods of charcoal producers (Schure *et al* 2013). For example, Tanzania's forest law indicates ways in which villages can obtain permission to use part of the forest on their village land for charcoal production and other commercial forest activities (Blomley 2006). The ecosystems in which charcoal is produced in tropical biomes range from shrubland (e.g., Namibia) (Stafford *et al* 2017), to dry tropical forests (e.g., miombo woodlands of Tanzania) (Malimbwi *et al* 2005) to tropical rainforests (e.g., tropical rainforests of the Democratic Republic of Congo) (Schure *et al* 2014). The social-economic settings under which charcoal is produced range from relatively poor in countries where charcoal is mainly produced as a household fuel, such as in Tanzania (Mwampamba 2007), to relatively wealthy in countries, where charcoal is mainly produced for industry, export, or where only a small percentage citizens rely heavily on charcoal as cooking fuel, such as Brazil (FAO 2017). Therefore, the variation in charcoal production systems around the world is triggered by specific social, economic and political settings, governance systems, users, resource units and ecosystems under which charcoal is produced. In this Chapter, I introduce common charcoal production systems in the tropics based on a non-exhaustive literature review. This overview of common charcoal production systems provides a starting point to identify possible transitions that may occur in charcoal production systems that could be analyzed to understand their impacts on forest use and livelihoods. The literature review of **Chapter 2** informs the studies of **Chapter 3** to **Chapter 7** of this thesis.

### *1. Charcoal production systems in the tropics*

In this thesis, I focus on the production side of the charcoal value chain; hence I exclude non-production aspects, such as the trade and transportation of charcoal to centers of demand. I define charcoal production systems as those with an input (i.e., woody biomass from trees or shrubs) that is converted (i.e., carbonization techniques to turn woody biomass into charcoal) into an output (i.e., charcoal biomass) that can be sold, and that is under a certain formal or informal governance (i.e., rules, regulations and societal norms for production) (**Figure 2.1**) (FAO 2017). Based on literature, I assessed the main differences in the four components of charcoal production systems. This non-exhaustive review revealed that charcoal production systems mainly differ in the intensity at which charcoal is produced and the access charcoal producers have to woody biomass resources to produce charcoal. I define charcoal production intensity as the amount of charcoal produced in a given area, and I define charcoal producer accessibility as the amount of natural forest or plantation biomass within a given area that can be accessed by a specific group of producers (e.g., members of communities or hired laborers). Production intensity is a function of charcoal demand (Ahrends *et al* 2010, Ghilardi *et al* 2018), and the amount of woody biomass available for production (Baumert *et al* 2016, Woollen *et al* 2016). For instance, areas with high forest availability close to centers of demand (e.g., a city) tend to experience high charcoal production intensity (Ahrends *et al* 2010, Woollen *et al* 2016). However, when forest availability drops, the time and effort it takes to produce charcoal drives up production costs, which causes a decrease in production in this area (Baumert *et al* 2016, Schaafsma *et al* 2014). On its turn, accessibility to woody biomass is controlled by country specific laws and by-laws at a national, regional and local level (FAO 2017). For instance, access to forest biomass may be controlled

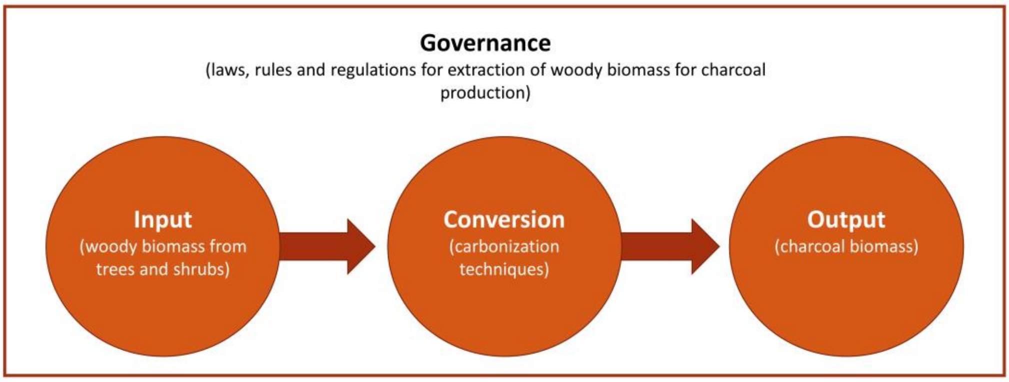
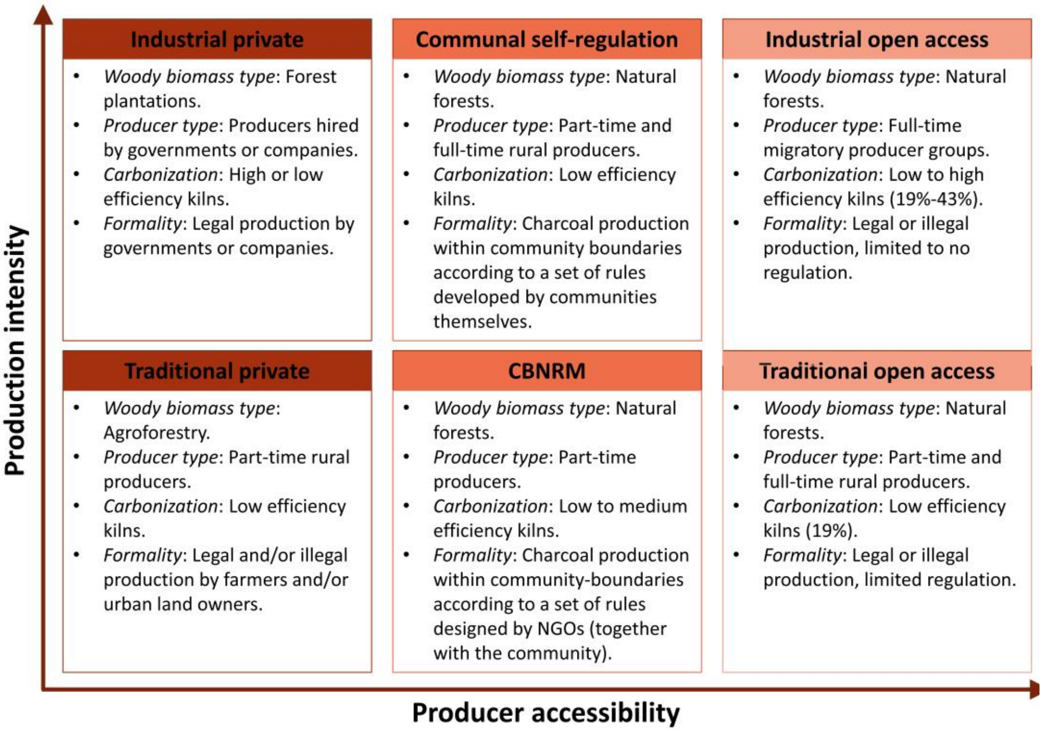


**Figure 2.1**. The charcoal production system and its components.

by national or sub-national organizations, by local communities within communal management systems (Ishengoma *et al* 2016, Robinson *et al* 2014b), or individuals and companies in private systems (Lejeune *et al* 2013, Piketty *et al* 2009).

Based on differences in charcoal production intensity and accessibility, I identified six charcoal production systems in the tropics along two main axes: (i) output: the intensity of charcoal production in weight that ranges between traditional (i.e., charcoal used as a cooking fuel and for small scale industry) and industrial output (i.e., charcoal used for large scale industry, such as the pig iron industry), and (ii) accessibility: the type of access charcoal producers have to woody biomass resources based on the laws, rules and regulations in place and the rights communities, individuals or companies have over trees, forests or plantations (**Figure 2.2**). In total we introduce six common charcoal systems in the tropics: two open access systems, including traditional open access and industrial open access, two communal management systems, including community-based natural resources management (CBNRM) systems and communal self-regulation, and two private systems, including traditional private systems and industrial private systems.



**Industrial private**
- *Woody biomass type*: Forest plantations.
- *Producer type*: Producers hired by governments or companies.
- *Carbonization*: High or low efficiency kilns.
- *Formality*: Legal production by governments or companies.

**Communal self-regulation**
- *Woody biomass type*: Natural forests.
- *Producer type*: Part-time and full-time rural producers.
- *Carbonization*: Low efficiency kilns.
- *Formality*: Charcoal production within community boundaries according to a set of rules developed by communities themselves.

**Industrial open access**
- *Woody biomass type*: Natural forests.
- *Producer type*: Full-time migratory producer groups.
- *Carbonization*: Low to high efficiency kilns (19%-43%).
- *Formality*: Legal or illegal production, limited to no regulation.

**Traditional private**
- *Woody biomass type*: Agroforestry.
- *Producer type*: Part-time rural producers.
- *Carbonization*: Low efficiency kilns.
- *Formality*: Legal and/or illegal production by farmers and/or urban land owners.

**CBNRM**
- *Woody biomass type*: Natural forests.
- *Producer type*: Part-time producers.
- *Carbonization*: Low to medium efficiency kilns.
- *Formality*: Charcoal production within community-boundaries according to a set of rules designed by NGOs (together with the community).

**Traditional open access**
- *Woody biomass type*: Natural forests.
- *Producer type*: Part-time and full-time rural producers.
- *Carbonization*: Low efficiency kilns (19%).
- *Formality*: Legal or illegal production, limited regulation.

**Figure 2.2**. Six common charcoal systems in tropical biomes ordered according to their expected level of production intensity and producer accessibility. The six systems can be divided in three groups: (i) private systems (left column), (ii) communal management systems (middle column), and (iii) open access systems (right column). The systems may occur simultaneously in the same area and/or may interact with each other. CBNRM = Community-based natural resources management.

## 1.1 *Open access systems*

I define open access systems as those systems in which charcoal producers can relatively freely access forest biomass due to a lack of or an inability to sufficiently uphold existing laws, rules and regulations.

- *Traditional open access systems* consist primarily of rural, usually part-time producers who harvest trees and shrubs from natural forests in the vicinity of their homes (Schaafsma *et al* 2014, Woollen *et al* 2016). Producers mostly operate individually or in small groups, resulting in scattered production sites throughout forests with a relatively low harvesting intensity (e.g. amount of charcoal production per unit area) (Vollmer *et al* 2017). Harvesting intensities typically range from 7,770 to 9,590 kg per producer per year (Baumert *et al* 2016). Charcoal biomass harvest might result from clear-cutting in the process to convert forest into agriculture (Iiyama *et al* 2017). Producers in traditional open access systems tend to build single use low efficiency transitional earth kilns (approximately 19% conversion efficiency (Chidumayo and Gumbo 2013)) in the vicinity of their harvesting area (FAO 2017). Producers operate either legally or illegally, dependent on whether national or sub-national policies exist that may or may not place restrictions on forest extraction and whether producers adherence to such restrictions (Schure *et al* 2013). Traditional open access systems occur throughout the tropics, predominantly in Sub-Saharan Africa, where charcoal production is largely informal (i.e., unofficial regulation of production) (Schure *et al* 2013). Examples of tropical countries in which illegal charcoal production takes place are Kenya (Iiyama *et al* 2017, Ruuska 2013, Sola *et al* 2021), Brazil (Brito and Barreto 2011, Glaser *et al* 2003, Otsuki 2012), Nigeria (Agunloye *et al* 2020, Ekhuemelo *et al* 2017, Meduna *et al* 2009) and Tanzania (Butz 2013, Sander *et al* 2013, Schaafsma *et al* 2012), Malawi (Smith *et al* 2015, 2017, Zulu 2010). At present, the extent to which illegal charcoal production occurs remains unknown at global scale (Schure *et al* 2013).

- *Industrial open access systems* consist of large-scale informal production, usually undertaken by migrating producers in natural forests, which labor for an urban-based investor (Kato *et al* 2004). Producers use low to medium efficiency kilns (19% to 46% conversion efficiency) built in the vicinity of the harvesting area (FAO 1983, 2017). The groups of full-time producers in industrial systems generate more charcoal per year than producers in traditional open access systems (Fearnside 1989); up to 231,000 kg per producer per year in Brazil (FAO 1983). Although these estimates are over 30 years old, a recent publication suggests that production in industrial open access systems continues to date (Sonter *et al* 2015). Industrial open access systems occur predominantly in Brazil, where 52.8% of charcoal that is produced for the pig iron industry (5.5 million tons in 2005) originates from this system (Ceccon and Miramontes 2008, Nogueira *et al* 2009). Examples of countries where this system occurs are Angola (Chiteculo *et al* 2018), Mozambique (Baumert *et al* 2016), Ethiopia (Iiyama *et al* 2017), Ghana (Amanor *et al* 2002), and Liberia (Jones 2015). Producers either act legally or illegally (Ceccon and Miramontes 2008, Schure *et al* 2013).

### *1.2 Communal management systems*

I define communal management systems as those in which forest resources are governed by a community either with guidance from external governance bodies (e.g., NGOs, and regional and national government agencies) or without guidance from external governance bodies.

- *Community-based natural resource management systems* consist of rural, mostly part-time producers who harvest tree biomass from natural forests within their community boundaries (Akoa *et al* 2007b, Mutune and Lund 2016). These systems operate under the guidance of (local) NGOs, which offer guidelines and knowledge on charcoal production and forest management (Ishengoma *et al* 2016, WB 2010b). Producers operate in small groups, which share knowledge on production (Ishengoma *et al* 2016, WB 2010b). Communities either use traditional kilns or adopt more efficient ones (Ishengoma *et al* 2016). Rules, regulations and by-laws to produce charcoal are established to assure efficient production that avoids deforestation and limits forest degradation, while increasing benefits for producers and the community as a whole (FAO 2017). Rules are designed to restrict access to forest biomass for producers from outside the community (Ishengoma *et al* 2016), and to assure harvesting intensities at levels that support forest recovery (e.g., a 24 year rotation regime) (Ishengoma *et al* 2016). Some communities do not focus their management specifically on charcoal, and here production is often banned or regulated through permits (Akoa *et al* 2007b, Mutune and Lund 2016). Community-based natural resources management is commonly practiced in Tanzania and Senegal (Doggart 2016, WB 2010b), while charcoal production is, for instance, banned in community-based natural resources management systems found in Cameroon (Akoa *et al* 2007b) and Kenya (Mutune and Lund 2016).
- *Communal self-regulation systems* are characterized by rural, mostly part-time producers that harvest biomass from natural forests within their community boundary under a set of rules and regulations, designed and uphold by communities themselves (Chingaipe *et al* 2015, Prasetiamartati *et al* 2008). Hence, no interference by external governance systems, such as NGOs or government agencies takes place in these systems. Producers mostly operate individually or in small groups, resulting in scattered production (Mongbo 2008, Prasetiamartati *et al* 2008). Although we did not find quantitative evidence for charcoal production intensity in these systems, some authors mention overharvesting (Chingaipe *et al*

2015). Therefore, we expect that the production intensity in these systems is generally higher than in community-based natural resources management systems. Producers use low efficiency kilns build in the vicinity of their harvesting area (Prasetiamartati *et al* 2008). The community implements a set of rules and regulations (e.g., permit systems), with the aim to reduce deforestation and forest degradation (Mongbo 2008, Prasetiamartati *et al* 2008). Evidence for this charcoal production system is scarce but it is found, among others in Indonesia (Prasetiamartati *et al* 2008), Benin (Mongbo 2008), Malawi (Chingaipe *et al* 2015), Mali (Gautier *et al* 2011), and India (Ghate and Nagendra 2005).

### *1.3 Private systems*

I define private systems as those where access to forest resources is restricted to a selected set of producers or a company, often on land that is either owned, leased and/or managed by the producer or company.

- *Traditional private systems* are characterized by rural part-time producers who harvest trees from their own private land or leased agricultural land (Mganga *et al* 2015). Similar to traditional open access systems, producers mainly build low efficiency kilns in the vicinity of the harvesting area (Kituyi 2004). Due to the private nature of ownership or tenure, the intensity of charcoal production in these systems is mostly unknown. However, since trees from which charcoal is produced grow complementary to crops, the intensity of production is likely low (Fouladbash and Currie 2015). Producers may act legally or illegally depending on their ownership rights. For instance, in Angola, all trees are state property, regardless of ownership rights for those who plant them (Chiteculo *et al* 2018). Hence, producers in Angola need to obtain a permit to produce charcoal from the trees they grow on their privately owned land (Chiteculo *et al* 2018). In contrast, in the Democratic Republic of Congo (DRC) and the Dominican Republic, governments actively promote the production of charcoal from agricultural land (Geilfus 1997, Gray 2017). Overall, we found evidence for this system in several tropical countries, such as Haiti (Gibbons 2010, Murray and Bannister 2004), India (Jambulingam and Fernandes 1986), Kenya (Andika *et al* 2014, Mganga *et al* 2015), and Liberia (Fouladbash and Currie 2015).
- *Industrial private systems* are characterized charcoal production from trees grown at large scale plantations (Pinto *et al* 2018), in which biomass harvest follows a rotation scheme, and trees are managed to promote intensive production (Fearnside 1989). At present, it is unclear which type of producers utilize plantation wood and we, furthermore, did not find an indicator for the efficiency of charcoal production in this system. Nevertheless, it is likely that conversion efficiency is high as companies likely would wish to produce as much charcoal on their plantation land as possible to reduce losses and ensure effiency. Companies or governments often own land where they legally plant fast growing trees, such as Eucalyptus (FAO 2017, Pinto *et al* 2018). The vast majority of plantations for charcoal production are found in Brazil, and this charcoal is mainly used for industrial purposes, specifically the pig iron industry (Piketty *et al* 2009). In the remaining tropics, plantations for charcoal are rare but they have been documented in the DRC (Gray 2017), Burkina Faso (Chauvin 1989), Ecuador (Luoma 2004), and Ethiopia (Mekonnen *et al* 2007).

It should be noted that individual cases in practice may not strictly fit in the above classification scheme and that numerous charcoal production systems may occur in the same area and/or interact with each other. For example, communal management systems may be affected by open access systems when producers from outside produce charcoal within community boundaries (Robinson *et al* 2014b). Although it is important to take the interactions and overlap between systems into consideration to understand the complexity of charcoal production in tropical biomes, this is beyond the scope of this Chapter. The main function of this Chapter is to provide background on the main charcoal production systems existing in the tropics, which informed the stylized modelling study of **Chapter 3**, and the selection of study areas in **Chapter 4** to **Chapter 7**.

# Chapter 3

## Long term impacts of transitions in charcoal production systems in tropical biomes

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**Chapter 2** reveals common charcoal production systems. This system overview allows us to identify possible transitions in charcoal production systems that aim at reducing charcoal-related deforestation and forest degradation and/or improve charcoal-supported livelihoods. Based on **Chapter 2**, the following questions may be asked: How do transitions influence the different components of the social-ecological systems framework and their interactions? Are certain transitions more effective than others in reducing deforestation and/or improving charcoal-supported livelihoods? And, does the initial state of the social-ecological system components affect outcomes of a charcoal system transition?

In **Chapter 3**, I explore the impact of transitions in charcoal production systems identified in **Chapter 1** and **Chapter 2** of this thesis on the interaction between two primary components, (i) related ecosystems (i.e., tropical forests and forest plantations), and (ii) resource units (i.e., forest and plantation biomass and charcoal biomass) over time. Hereby, I account for the economic settings of the charcoal system by addressing effects of varying levels of demand on interactions between the three components named above. I explore these dynamics theoretically through a stylized social-ecological model that simulates feedbacks between woody biomass resources growing in tropical forests and forest plantations and the charcoal biomass produced from it. I model in a fixed modelling environment (i.e., the resource system), with a fixed number of producers (i.e., the users).

**Figure 3.1** provides an overview of the social-ecological system components assessed in **Chapter 3**, their interactions, and the studied transitions in charcoal production systems. The **Supplementary Materials** of **Chapter 3** can be found in the **Appendix of Chapter 3** of this thesis.

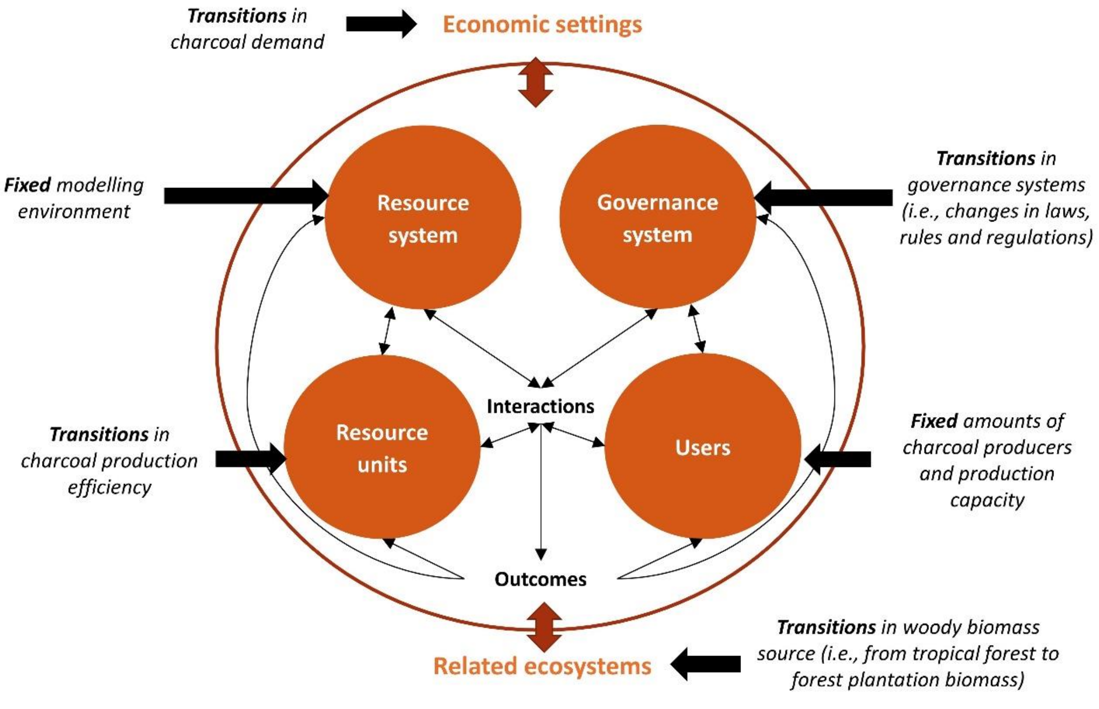

**Figure 3.1.** The social-ecological system components assessed in **Chapter 3**, their interactions, and the studied transitions in charcoal production systems.

**Published scientific paper**

# Long term impacts of transitions in charcoal production systems in tropical biomes

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Keywords: Charcoal, social-ecological systems, forest biomass, feedbacks, management

## Abstract

Mitigation of greenhouse gas emissions through transitions to biomass-based renewable energy may result in higher land needs, affecting ecosystem services and livelihoods. Charcoal is a biomass-based renewable energy that provides energy for hundreds of millions of households worldwide and generates income for 40 million people. However, it currently causes up to 7% of the global deforestation rate. In the absence of affordable alternative fuels, it is necessary to identify conditions that foster sustainable charcoal production. In this study, we (i) develop a stylized model that simulates feedbacks between forest biomass and charcoal production, and (ii) use the model to examine the effects of interventions that foster sustainable charcoal systems through transitions to communal management or private systems, increases in carbonization efficiency and charcoal demand reductions. Our model simulations suggest that at low demand, a transition is unnecessary. At intermediate to high demands, interventions that increase carbonization efficiency and/or reduce demand should be combined with transitions to communal management (at intermediate forest biomass levels) or private systems (at low forest biomass levels) to ensure long-term sustainability of charcoal systems and avoid collapse within 100 years. These results highlight multiple pathways for sustainable charcoal production systems tailored to meet supply and demand. They are all pathways that are feasible across tropical biomes and could foster the simultaneous continuation of forests and charcoal production in the near future.

## 1. Introduction

Globally, mitigating greenhouse gas emissions through transitions to biomass-based renewable energy results in higher land needs and affects ecosystems, their services and livelihoods (Heck *et al* 2018). Charcoal is one of these controversial biomass-based renewable energies, produced in complex social-ecological systems around the world (FAO 2017). Charcoal production contributes to up to 7% of global deforestation annually and forest degradation (Chidumayo and Gumbo 2013). Charcoal provides energy for hundreds of millions of people worldwide and income for 40 million people (Schure, Levang, and Wiersum 2014; Baumert et al. 2016; FAO 2017; Agyei, Hansen, and Acheampong 2018). A 5% increase in charcoal demand is predicted by 2100, due to growing urban populations in Sub-Saharan Africa (Hillring 2006, IEA 2014, Santos *et al* 2017). Charcoal production occurs mostly in open access systems in which charcoal producers freely access forest biomass under limited (adherence to) rules and regulations (FAO 2017). Therefore, the projected increase in charcoal production will likely cause additional deforestation (Specht *et al* 2015, Santos *et al* 2017) and reduced socioeconomic benefits for producers (Baumert *et al* 2016, Woollen *et al* 2016, Vollmer *et al* 2017).

Transitions towards sustainable charcoal production systems are necessary to mitigate negative impacts on forest biomass and livelihoods (Luoga *et al* 2000, Mwampamba 2007). Due to high demands for affordable and reliable energy in the tropics, it is likely that transitions from charcoal to alternative energy sources, such as gas, will take time and resources (FAO 2017). At present, several interventions exist that promote a transition towards sustainable charcoal production systems applied at different stages of the charcoal production cycle, as a standalone intervention and/or in combination with other interventions (FAO 2017). Interventions aim for:

(i) A transition from open access to alternative systems to reduce deforestation and forest degradation (Lejeune *et al* 2013, Ishengoma *et al* 2016), e.g. by introducing permit systems, adding private forest plantations, or switching to community-based natural resources management (CBNRM) (FAO 2017, Syampungani *et al* 2017).

(ii) An external input to livelihood assets of producers to increase charcoal production efficiency by introducing efficient kilns, i.e. carbonization ovens for charcoal production (Bailis 2009).

(iii) A decrease in demand by promoting sustainable consumption and the use of alternative energies (Kojima 2011, Broto *et al* 2018) by promoting alternative fuels, such as gas (Kojima 2011, Broto *et al* 2018) and introducing efficient cooking stoves (Mwampamba *et al* 2013, Dagnachew *et al* 2020).

Currently, it is unclear whether interventions that aim for a transition to more sustainable charcoal production achieve their objectives (Mwampamba *et al* 2013). One way to better understand the potential effects of different interventions on forests and charcoal production is through social-ecological modelling. Social-ecological models are used to capture complex system dynamics (An 2012). Previous modeling studies have examined the role of interventions and their effects in charcoal systems (Robinson *et al* 2012). For example, modeling a transition towards community forest management in South-West Cameroon showed a positive influence on charcoal producer revenues (Akoa *et al* 2007a). A modelling study of Robinson et al (2012) in Tanzania showed that interventions such as promoting legal forest extraction by charcoal producers and involving them in law enforcement reduced forest degradation. A spatially-explicit simulation of woodfuel extraction in Haiti showed that aggressive interventions may reduce or even reverse charcoal-driven forest degradation allowing forests to recover (Ghilardi *et al* 2018). While these models provide important information on charcoal systems, existing models focus on case studies in relatively small regions and often simulate only one or a narrow range of interventions.

In this study, we develop a stylized social-ecological model that simulates feedbacks between charcoal production and forest biomass to understand the general dynamics of charcoal systems in the tropics. We use this model to examine the effect of a set of interventions, i.e., transitions from open access systems to communal management and private systems on this feedback and identify the conditions under which interventions result in sustainable production systems. Hereby, we define communal management systems as those in which forest resources are regulated by communities (e.g. CBNRM), and private systems as those where access to forest resources is restricted to a selected set of producers (e.g. plantations and agroforestry).

## 2. Methods

We developed a model that simulates the feedback between charcoal biomass (Units: Mg) and forest biomass (Mg). The model provides a simplified non-spatial, analytically tractable representation of charcoal production systems over time (An 2012). Therefore, we did not model specific real-world systems, and did not specify decisions by individual actors but simulated the actions of a group of individuals collectively. The aim of our simulations was to discover (i) whether a system transition results in a change in forest and charcoal biomass dynamics and (ii) if the timing of transition influences these dynamics. We developed the model in MATLAB.

### 2.1 Model environment

We considered an area of 10,000 ha and used long-term simulations (1,000 years) to assess the potential for steady social-ecological system states to emerge (***Figure 1***). We simulated 1,000 years because it reflects long-term effects of interventions and we could observe when and whether systems reach a stable state. We initialized the model with 50% forest cover, assuring availability of sufficient woody biomass for multiple people to produce charcoal simultaneously. In private systems, charcoal is

**Table 1.** Model parameters, definitions and value ranges based on literature. See the content of Supplementary Materials A for an argumentation for each parameter range/value.

| Parameter | Parameter definition | Initialization |
|---|---|---|
| $B_{f\ (initial\ value)}$ | Tropical forest and plantation biomass (Mg) | *Forest*: 449,500 Mg<br>*Plantation*: 367,600 Mg |
| $B_{c\ (initial\ value)}$ | Charcoal biomass (Mg) | 1,260 Mg |
| $m$ | Maximal wood harvest in open access systems (Mg.year$^{-1}$) | 28,906 Mg.year$^{-1}$ |
| $m_c$ | Harvesting rate in communal management systems (year$^{-1}$) | *Communal*: 0.009 year$^{-1}$ |
| $m_p$ | Harvesting rate in private systems (year$^{-1}$) | *Private*: 0.043 year$^{-1}$ |
| $D$ | Maximal demand (Mg) | 100,000 Mg.year$^{-1}$ |
| $v$ | The forest biomass level at which half of the maximal charcoal carrying capacity is reached (Mg.year$^{-1}$) | 73,100 Mg.year$^{-1}$ |
| $g$ | Growth rate of tropical forest and plantation biomass (year$^{-1}$) | *Forest*: 0.0086 year$^{-1}$<br>*Plantation*: 0.0426 year$^{-1}$ |
| $x$ | The production capacity / demand level at which half of the maximal harvest is reached (Mg.year$^{-1}$) | 2,517 Mg.year$^{-1}$ |
| $K$ | Carrying capacity of natural forests and plantations (Mg) | *Forest*: 1,949,000 Mg<br>*Plantation*: 416,000 Mg |
| $c$ | Carbonization efficiency of earth-mound kilns | 0.19 |
| $\delta_p$ | Depreciation rate of charcoal production (year$^{-1}$) | 0.5 year$^{-1}$ |
| $n$ | Population growth rate (year$^{-1}$) | 0.019 year$^{-1}$ |
| $q$ | Time | 1 year |

produced from plantation biomass. We assumed that plantation biomass already exists within our model area, complementary to natural forests. We assumed that 20% (2,000 ha) of the modelling area is covered with plantations at the start of each simulation. ***Table 1*** includes the parameterization of the model adhered to in this article. ***Supplementary materials A*** includes justifications for the model parameterization, derived from empirical studies of charcoal production systems in Sub-Saharan Africa, augmented with data from other regions.

### 2.2 Simulating charcoal and forest biomass

We defined forest biomass as the total weight of woody plant material in a given area, and charcoal biomass by weight. For all systems, we assumed that forest biomass increases over time through natural regeneration (Hofstad and Araya 2015), and decreases due to harvesting to produce charcoal. The charcoal biomass produced depends on the carbonization efficiency from wood to charcoal (FAO 2017). Hence, we calculated charcoal production by multiplying harvested forest biomass with the carbonization efficiency. We alternated the carbonization efficiency to assess its impact on forest and charcoal biomass. We assumed that charcoal biomass depreciates as a function of the depreciation rate (i.e. consumption within centers of demand outside the production area) and urban population growth (following the Solow model of supply and demand (Solow 1956)). The feedback between natural forest biomass and charcoal biomass was modelled as:

$$\frac{dB_f}{dt} = G - H \tag{1}$$

$$\frac{dB_c}{dt} = cH - (\delta_p + n)B_c \tag{2}$$

In Eq. (1), $B_f$ is forest biomass (Mg), t time (years), $G$ growth of forest biomass (Mg.year$^{-1}$), $H$ the forest biomass harvested (Mg.year$^{-1}$). In Eq. (2), $B_c$ is charcoal biomass (Mg), $c$ is the carbonization efficiency of forest biomass into charcoal (-), $\delta_p$ depreciation rate of charcoal (year$^{-1}$), and $n$ human population growth rate (year$^{-1}$). Plantation biomass was modelled similar to forest biomass (Eq. (1)), but with a different growth and harvest level.

### 2.3 Simulating forest and plantation growth

We used a standard Verhulst function to model the growth of natural forest biomass over time (Hofstad and Araya 2015):

$$G = gB_f(1 - \left(\frac{B_f}{K}\right)) \tag{3}$$

, where $G$ is the growth of forest biomass (Mg.year$^{-1}$), $g$ the growth rate of forest biomass (year$^{-1}$), and $K$ the carrying capacity of forest biomass (Mg). Growth of plantation biomass was modelled similar to forest biomass (Eq. (3)), but with a different growth rate.

### 2.4 Simulating production capacity

The main driver of charcoal production is demand (i.e. the amount of charcoal that is consumed per year) from urban centers and industry (FAO 2017). Demand for charcoal varies greatly between regions (Ahrends *et al* 2010) and countries (UN 2019). Besides this, charcoal production is dependent on woody biomass availability (Schaafsma *et al* 2014), because charcoal production becomes time consuming and less profitable at low forest biomass levels (Woollen *et al* 2016). Together, demand levels and forest biomass availability determine the charcoal production capacity (i.e. the amount of charcoal that is economically viable to produce) (Ghilardi et al. 2011). Production capacity decreases with the charcoal biomass, i.e. more charcoal left equals lower production capacity. We modeled production capacity as:

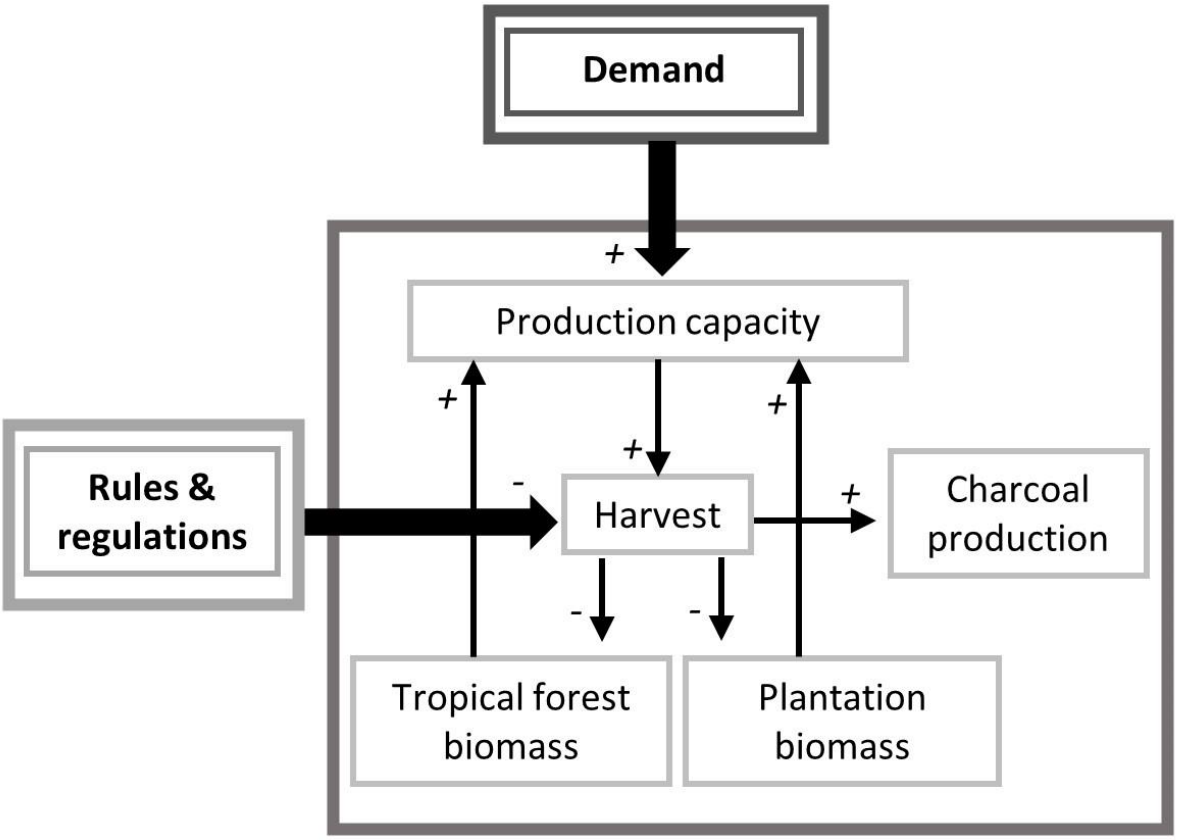

**Figure 1.** A stylized charcoal model, which considered an area of 10,000 ha of which 5,000 ha was forested at the initial model condition. All relationships are based on literature. + = Positive effect, - = Negative effect. Rules & regulations refers to rules and regulations implemented by governments, NGOs and companies with the aim to reduce the level of access users have to specific types or amounts or woody biomass recourses. Production capacity indicates the amount of production that is viable given a particular demand and woody biomass level.

$$P = \frac{DB_f^2}{(v^2+B_f^2)} - \frac{B_c}{q} \tag{4}$$

, where $P$ is the production capacity of charcoal (Mg.year$^{-1}$), $D$ is demand (Mg.year$^{-1}$), $v$ is the forest biomass level at which half of the maximal demand is reached (Mg.year$^{-1}$), and $q$ is time (year). For systems in which charcoal is produced from plantation forests, production capacity does not depend on natural forest biomass but on plantation biomass. We simulated reductions in demand by decreasing demand with fixed amounts per time step. Because of a projected 5% increase in charcoal demand by 2100 (Hillring 2006, IEA 2014, Santos *et al* 2017), we also explore the impact of rising demand by increasing it with fixed amounts per timestep.

### 2.5 Simulating woody biomass harvesting

Production capacity drives harvesting rates of woody biomass (i.e. the amount of above-ground woody biomass used for charcoal production per time step). We assumed a maximal charcoal biomass that a producer can/chooses to produce in open access systems because of the available time producers can spend on charcoal production (Brouwer and Magane 1999, Schaafsma *et al* 2014, Woollen *et al* 2016). We assumed that the amount of charcoal produced in open access systems depends on the production capacity and the maximal amount of charcoal that can be produced given the number of producers operating in the area. Hence, we modeled forest biomass harvest in open access systems as:

$$H = \frac{mP^2}{(x^2+P^2)} \tag{5}$$

, where $H$ is forest biomass harvested in open access forests (Mg.year$^{-1}$), $m$ the maximal forest biomass that can be harvested (Mg.year$^{-1}$), and $x$ the production capacity / demand level at which half of the maximal harvest is reached (Mg.year$^{-1}$).

### 2.6 Transitions in charcoal production systems

We simulated transitions from open access to communal management and private systems after 20, 100 and 500 years. We simulated both instantaneous transitions to assess the impact of purely communal management or private systems on forest and charcoal biomass, as well as more gradual transitions implemented in time steps. At instant transitions, the first 20, 100 or 500 years were simulated under open access systems after which a transition to communal management or private systems took place. Gradual transitions to communal management and private systems were modelled by transitioning open access system in stages. Hereby, we assumed that the share of charcoal production from communal or private systems increased by 20% after every 10 years, while charcoal production from open access systems decreased by the same amount. A complete transition towards a 100% communal management or 100% private system was thus reached in 5*10 = 50 years. We assumed that production in these systems reduces demand for charcoal produced from open access systems (Carvalho and Bacha 2010, Pinto *et al* 2018).

We assumed that charcoal producers in communal management systems are motivated by charcoal demand in a similar fashion to open access systems. However, harvesting restrictions limit charcoal production over time (Ghate and Nagendra 2005, Gautier *et al* 2011). Since the aim of communal management is to protect forests (Mongbo 2007, Chingaipe *et al* 2015), we assumed that harvesting rates allow for forest recovery. Hence, the harvesting rate remains below the forest growth rate in our simulations. We modeled biomass harvesting for charcoal production in communal management as:

$$H_c = \frac{m_c B_f P^2}{(x^2+P^2)} \qquad (6)$$

, where $H_c$ is the biomass harvested in forest under communal management (Mg.year$^{-1}$), $m_c$ the harvesting rate in communal management (year$^{-1}$).

For private systems, we assumed charcoal production from actively managed plantations planted outside natural forestland. We assumed that the plantations in our modelling area were in different growth stages allowing for continued harvesting, with harvest rates depending on the plantation growth rate. Because plantations are stationary and managed, reductions in plantation biomass do not influence time investments overall. We assume that plantation systems respond directly to demand, which depends upon the amount of charcoal in the system over time. Hence, we modelled biomass harvesting for charcoal production in private systems as:

$$H_p = \frac{m_p B_f (D - \frac{B_c}{q})^2}{(x^2+D^2)} \qquad (7)$$

, where *Hp* is the biomass harvested in plantations (Mg.year$^{-1}$) and $m_p$ the harvesting rate in private systems (year$^{-1}$).

## 3. Results

### 3.1 Effect of demand on open access system dynamics

We show the effect of changing demand on forest and charcoal biomass in open access systems after 20 years in ***Figure 2***. We modeled different trajectories with varying demand (10 Mg.year$^{-1}$ – 100,000 Mg.year$^{-1}$), with light gray trajectories indicating high demand and dark gray trajectories low demand. At low production intensity, charcoal biomass stability emerges rapidly. Forest biomass increases for approximately 500 years before it stabilizes at demand levels of 10 and 20,000 Mg.year$^{-1}$. At demands of 40,000 Mg.year$^{-1}$, forest biomass stabilizes after more than 1,000 years. At high demand levels (> 60,000 Mg.year$^{-1}$), forest biomass almost completely depletes, caused by a sharp rise in charcoal biomass levels in the first decades at the expense of forest biomass, followed by a rapid decrease to low charcoal biomass after 100 to 200 years. Temporal variations in demand cause larger variations in charcoal biomass than in forest biomass and have more impact at low initial demand levels (***Supplementary materials Figure B1***).

### 3.2 System transitions

We display a transition from open access systems to communal management or private systems by a switch from a solid to a dashed trajectory in ***Figure 2***. Our simulations show that a transition to communal management or to private systems mitigates forest biomass loss over time at all intensities (***Figure 2***). We find that a complete transition towards private systems results in a restoration of forest biomass after 1,000 years, even at high demands. On the other hand, the restoration of forest biomass in communal management systems depends on demand levels, with a stabilization of forest biomass after 500 years at low demands and after > 1,000 years at high demands. Temporal variations in demand cause larger variations in charcoal biomass than in forest biomass and have more impact at low demand (***Supplementary materials Figure B1***).

We find that the effect of a system transition depends on the timing of transition, with a fast increase in forest and charcoal biomass upon a transition after 20 years (***Figure 2***), and a slow increase upon a transition after 500 years (***Supplementary materials Figure B2***). Upon an early transition (after 20 years) to communal management, charcoal biomass is largest at high demand (> 60,000 Mg.year$^{-1}$). In

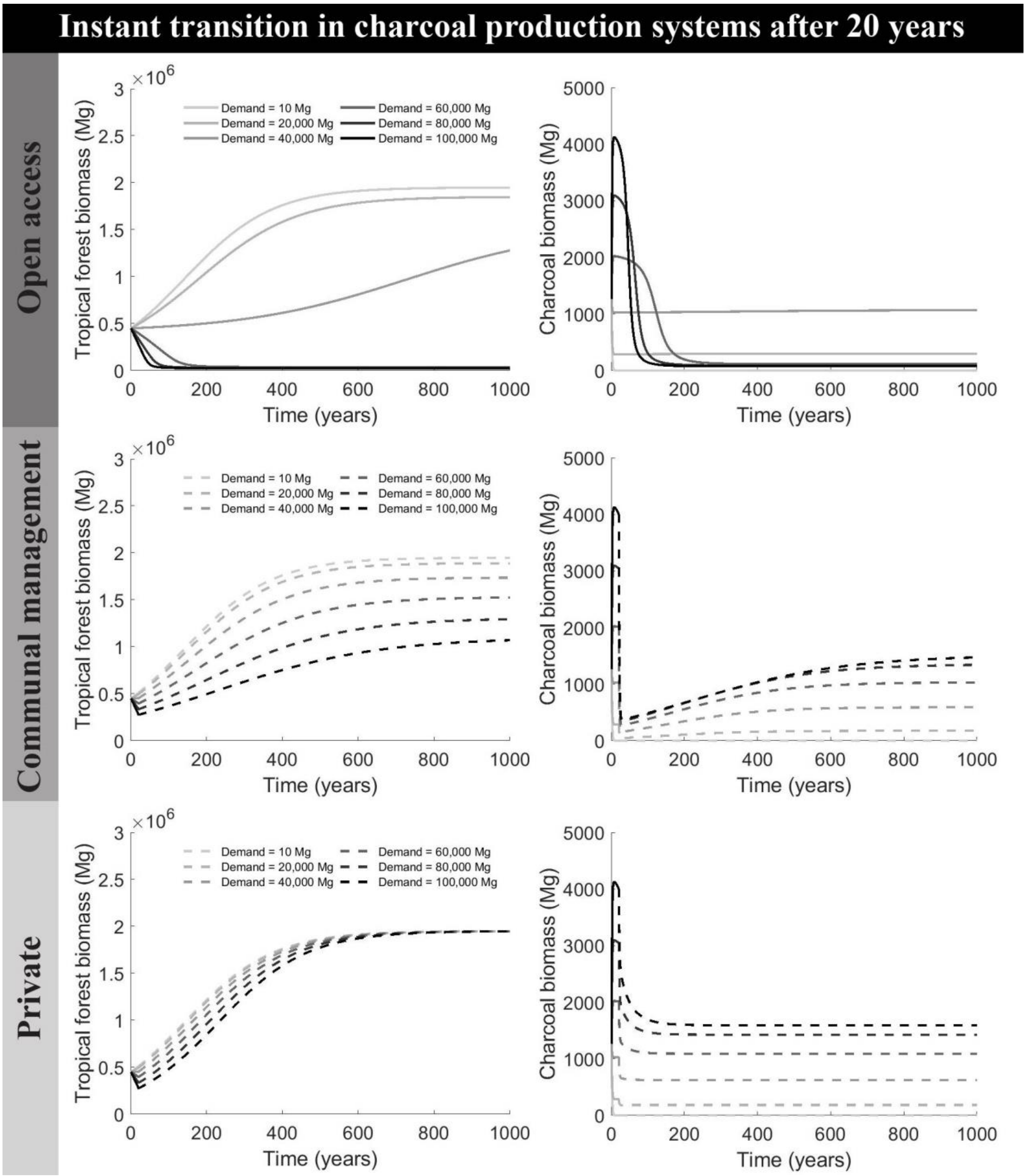

**Figure 2.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of demand (10 to 100,000 Mg.year$^{-1}$ in steps of 10,000 Mg). Every line indicates a certain level of demand (see legends). The level of demand is indicated by different gray tones, from light gray for low demands to black for high demands. A transition from an initially open access system after 20 years is simulated for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

systems where the transition takes place after 500 years, we observe that the highest levels of charcoal biomass are produced at intermediate demand (±40,000 – 60,000 Mg.year$^{-1}$) on a short term. However, on a long term (> 900 years) largest charcoal biomass levels are found at high demand.

***Figure 3*** shows the impact of a relatively slow transition in 4 steps spread over 50 years on forest and charcoal biomass for varying demand levels (10 Mg.year$^{-1}$ – 100,000 Mg.year$^{-1}$). A slower transition has limited consequences for forest biomass on the short term, but forests recover slower than upon an instant transition. Upon a slow transition, we observe

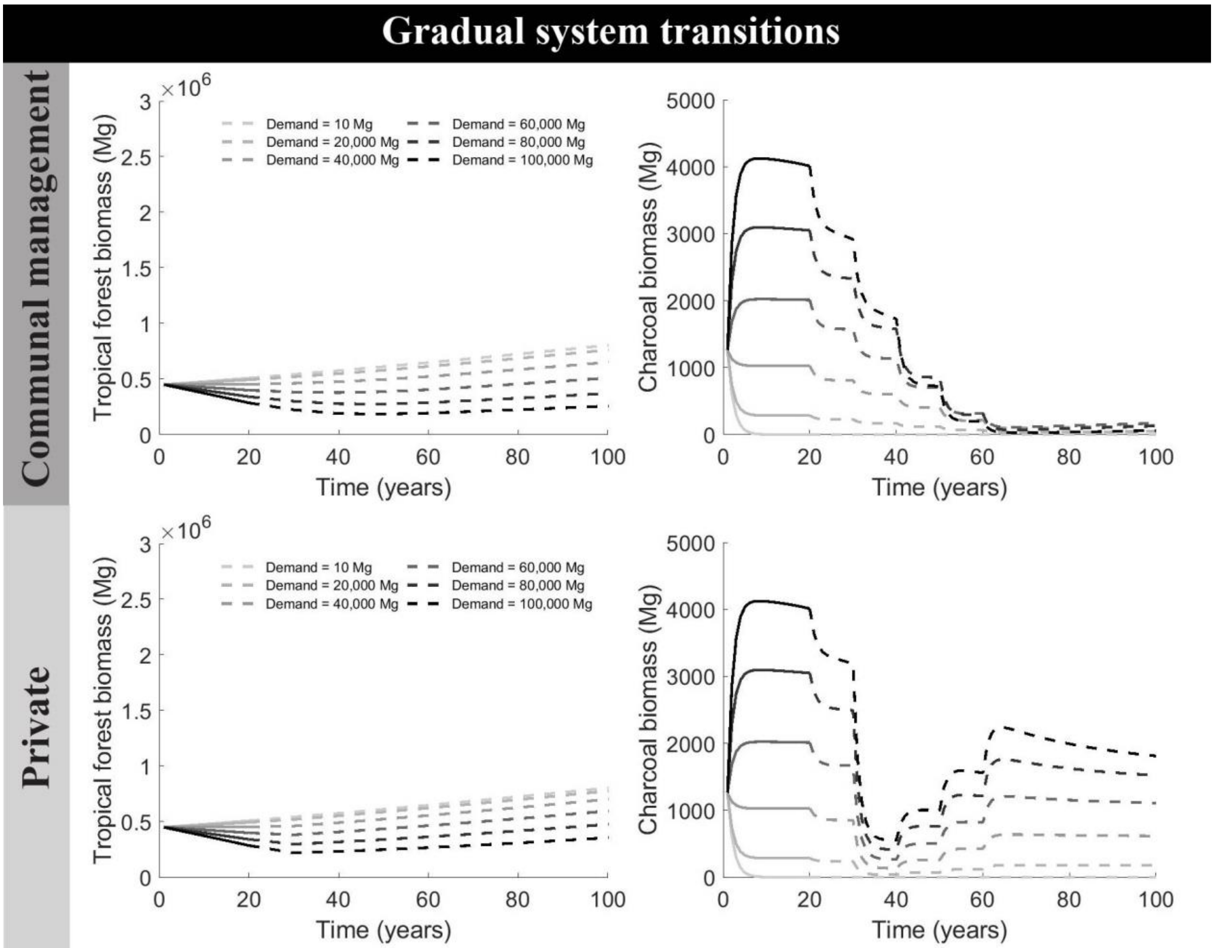

**Figure 3.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of demand (10 to 100,000 Mg year$^{-1}$ in steps of 10,000 Mg). Every line indicates a certain level of demand (see legends). The level of demand is indicated by different gray tones, from light gray for low demands to black for high demands. A gradual transition from an initially open access system after 20 years is simulated in5 subsequent steps of 10 years for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

a gradual decrease in charcoal production for communal management systems (500 – 800 Mg per 10 year transition step) as opposed to private systems, which experience a gradual increase (500 – 800 Mg per 10 year transition step).

### 3.3 Charcoal production efficiency

Increasing carbonization efficiency from 20% to 60% in open access systems at a demand level of 42,000 Mg.year$^{-1}$ positively impacts forest biomass, causing a gradual rise in forest biomass for more than > 1,000 years (***Figure 4***) and a continuous increase of charcoal biomass over time. However, at high levels of demand (> 60,000 Mg year$^{-1}$), the beneficial effects of promoting carbonization efficiency on forest and charcoal biomass disappear (***Supplementary materials Figure B3***). Unlike open access systems, forest biomass in communal management is largely unaffected by carbonization efficiencies but increases in production efficiency allow for higher charcoal biomass over time. In private systems, high production efficiency sustains higher charcoal biomass levels over time.

### 3.4 Changes in demand

Effects of increases in demand (50 Mg.year$^{-1}$) on forest biomass in open access systems are visible on long timescales, after ±200 years for medium demand (40,000 Mg.year$^{-1}$) and ±400 years for low initial demands (10 – 20,000 Mg.year$^{-1}$) and are characterized by a gradual decrease in forest biomass (***Figure 5***). Effects of increases in demand are immediately visible on charcoal biomass for low to medium demand (limited effect seen at high demand) and are characterized by a gradual increase in charcoal biomass for low demands (10 – 40,000 Mg.year$^{-1}$) and a gradual increase followed by a sharp drop in charcoal biomass after ±300 years for demand levels of 60,000 Mg.year$^{-1}$. Upon a transition to communal management systems, increases in demand only slightly affect forest biomass showing a slight decrease after ±500 years for low to medium initial demands (10 – 60,000 Mg.year$^{-1}$), while charcoal biomass increases gradually over time for these demands. We only observed a gradual increase in charcoal biomass for low to medium demand levels (10 – 60,000 Mg.year$^{-1}$) upon a demand increase in private systems.

We show the effect of gradual reductions in demand (reductions of 200 Mg.year$^{-1}$, 100 Mg.year$^{-1}$, and 50 Mg.year$^{-1}$) on forest and charcoal biomass in ***Figure 6*** and ***Supplementary materials Figure B4 and B5***. At the start of each simulation, demand starts at a fixed level, after which it declines yearly. Annual reductions in demand mitigate forest biomass loss in

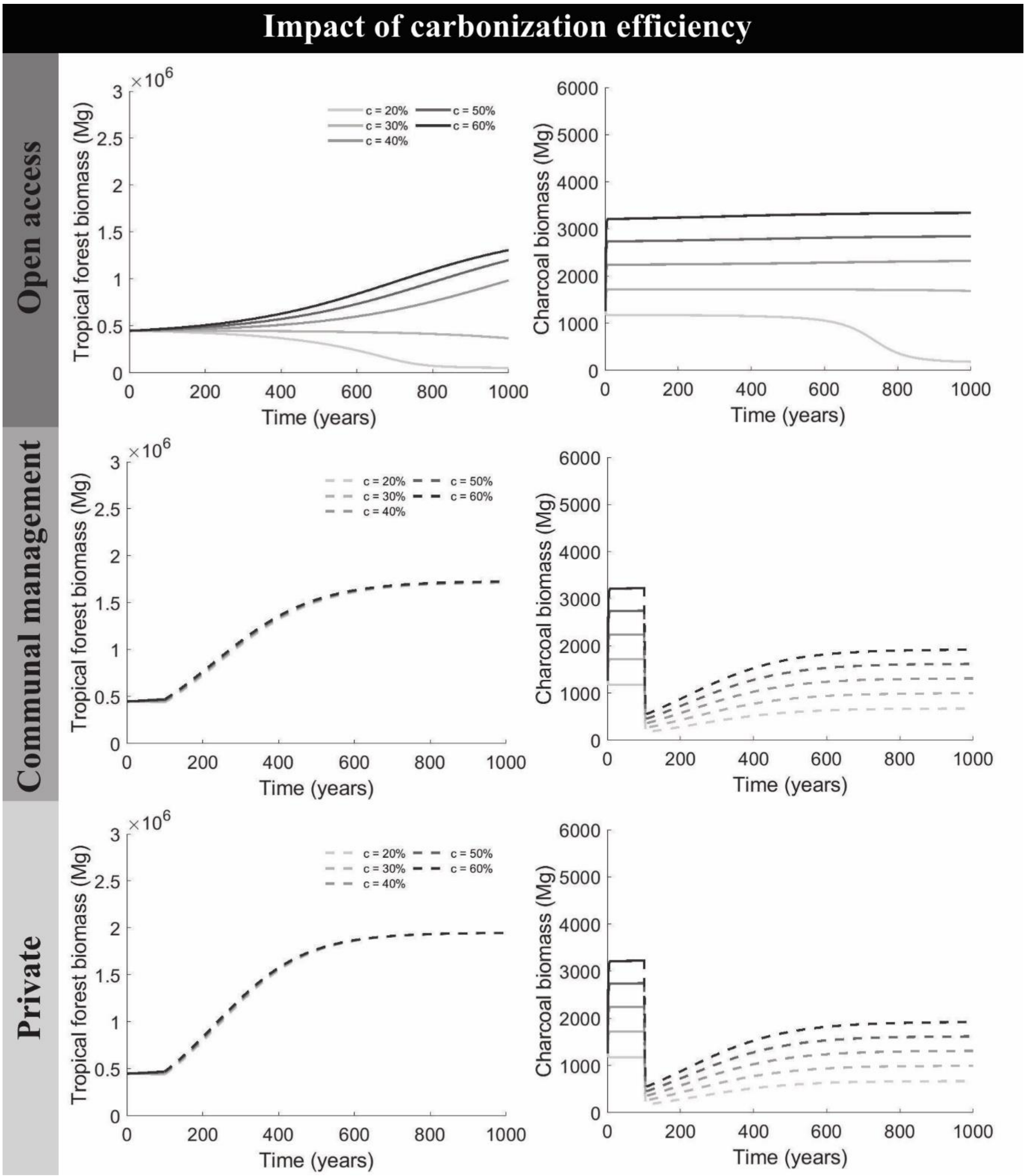

**Figure 4.** Topical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of carbonization efficiency (c). Every line indicates a certain level of carbonization efficiency (see legends). The carbonization efficiency is indicated by different gray tones, from light gray for low carbonization efficiencies to black for high carbonization efficiencies. A transition from an initially open access system after 100 years is simulated for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article). Demand levels in this simulation are set at 42,000 Mg.

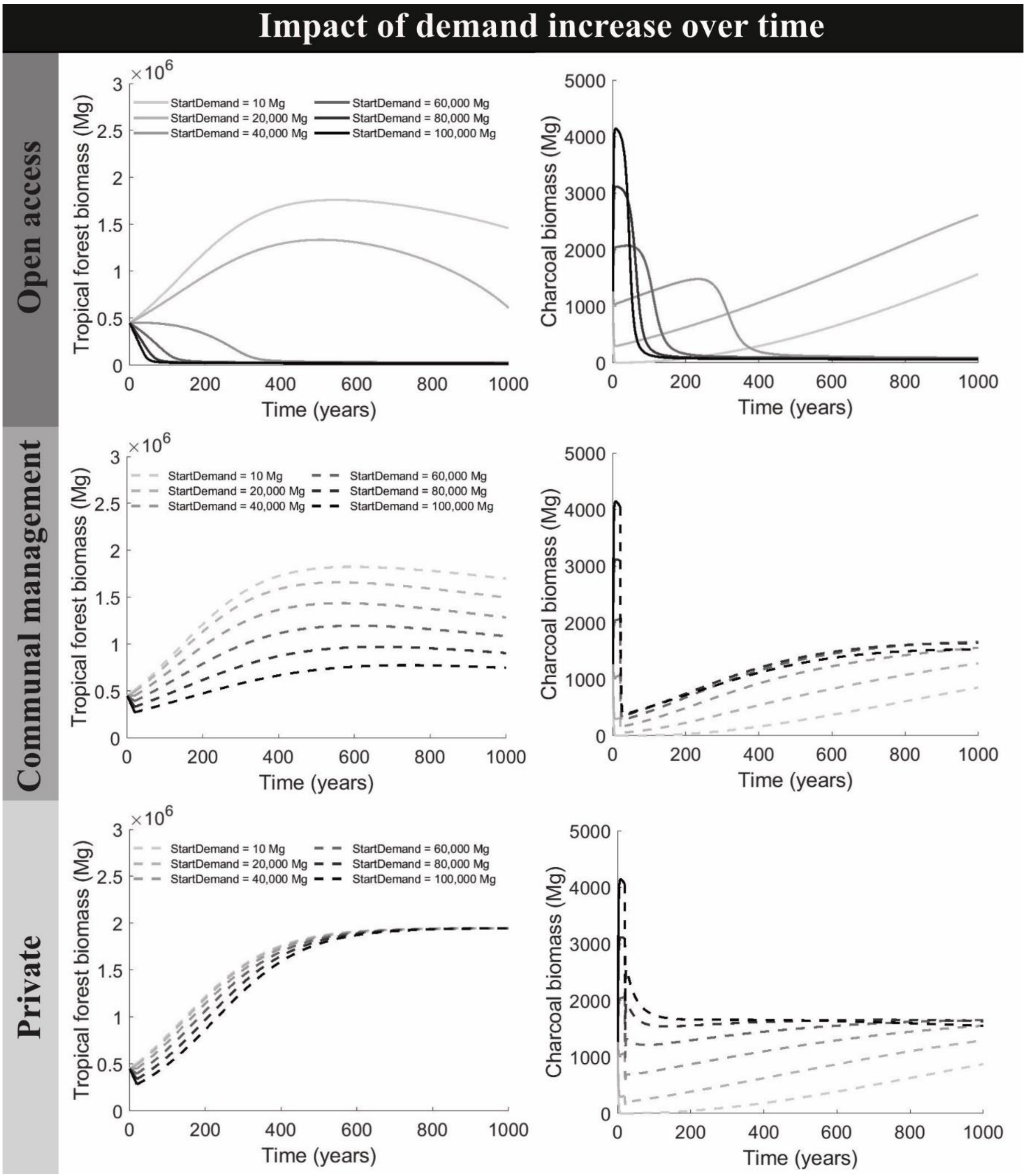

**Figure 5.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production simulated along a gradient of declining demand. The level of demand starts at 10 to 100,000 Mg.year$^{-1}$ (see legends; StartDemand) and demand subsequently increases with 50 Mg.year$^{-1}$ to simulate the potential impact of an increase in demand over time (as has been predicted by Santos *et al.* (2017)). Every line indicates a certain level of demand. A transition from an initially open access system after 20 years is simulated for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

open access systems that experience high levels of demand at the start of the simulation (>60,000 Mg.year$^{-1}$). Restoration of forest biomass commences only after 800 years upon a demand reduction of 50 Mg.year$^{-1}$, while it takes ½ that time (400 years) when demand is reduced by 100 Mg.year$^{-1}$, and ~¼ that time (250 years) when demand is reduced by 200 Mg.year$^{-1}$.

Under communal management, limited charcoal is produced with demand reductions of 100 Mg.year$^{-1}$ and 200 Mg.year$^{-1}$. However, at an annual demand reduction of 50 Mg.year$^{-1}$, charcoal production may

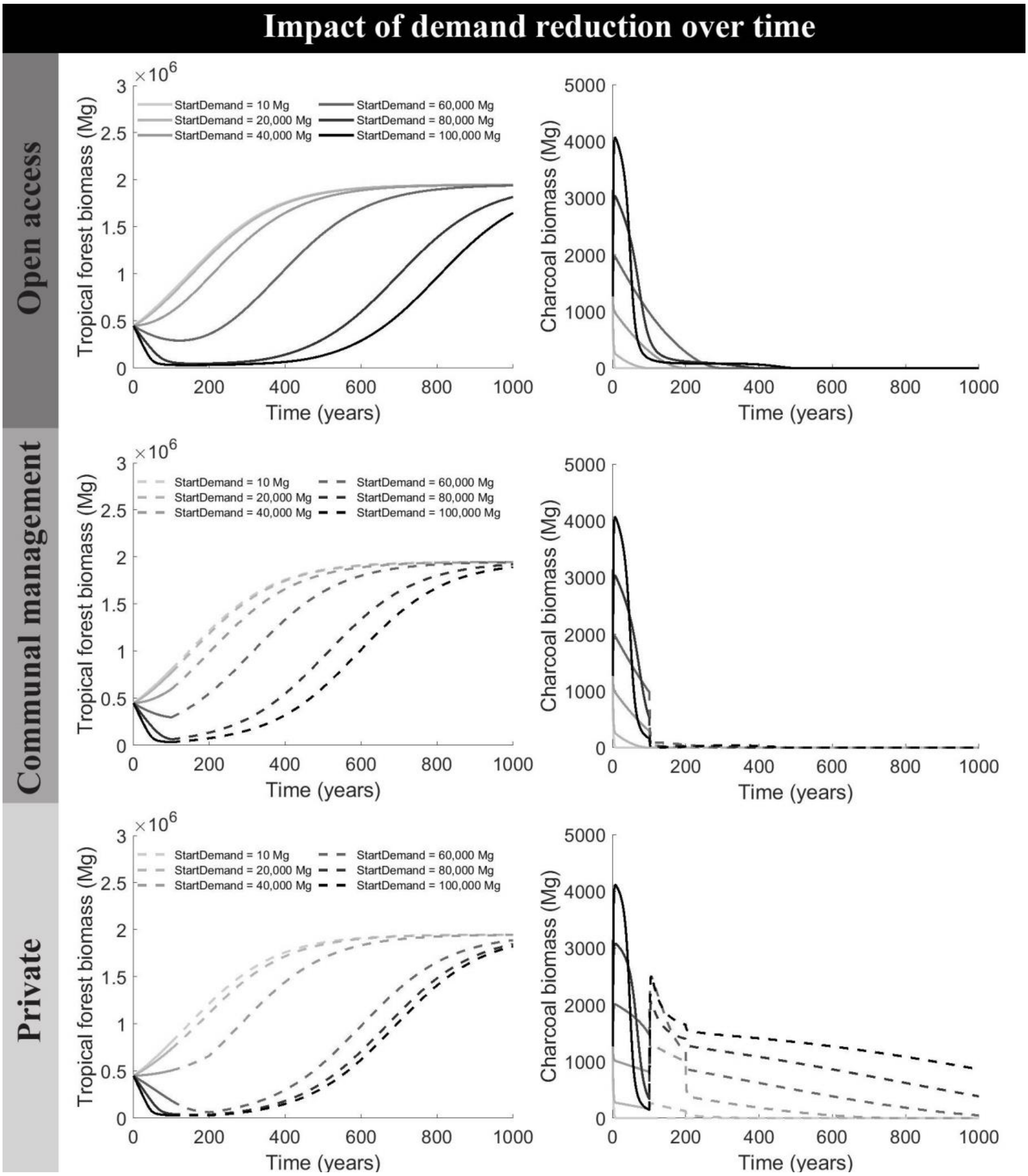

**Figure 6.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production simulated along a gradient of declining demand. The level of demand starts at 10 to 100,000 Mg.year$^{-1}$ (see legends; StartDemand) and demand subsequently declines with 200 Mg.year$^{-1}$ to simulate an intervention that reduces demand over time. Every line indicates a certain level of demand. A transition from an initially open access system after 100 years is simulated for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

continue for more than 1,000 years at high levels of initial demand (> 60,000 Mg.year$^{-1}$). In private systems, a reducing demand does not affect forest biomass and charcoal production continues for more than 1,000 years when high levels of demand (> 60,000 Mg.year$^{-1}$) are experienced at the start of the simulation, even at annual demand reductions of 200 Mg.year$^{-1}$.

### 3.5 Sensitivity analysis

Models are sensitive to changes in parameter values. Although we aimed for realistic assumptions and parameter ranges based on literature, parameterization influences results. We provide a sensitivity analysis in ***Supplementary materials C*** and find that our model simulations are robust to parameter value changes. The model is, however, sensitive to forest carrying capacity, which influences the amount of biomass an area of forest can harbor (*K*).

## 4. Discussion

We examined the impact of interventions aiming to promote transitions towards charcoal production systems that sustain both forests and charcoal-supported livelihoods. Our simulations show many pathways towards sustainable charcoal production and indicate that a combination of interventions is desirable at high demands.

### 4.1 Effect of demand on open access system dynamics

The simulated peak in charcoal production at high demands followed by a collapse of charcoal and forest biomass to low levels is supported by Woollen et al. (2016), Baumert et al. (2016) and Schaafsma et al. (2014). In the open-access charcoal production systems of the Mabalane district of Mozambique, Woollen et al. (2016) and Baumert et al. (2016) showed that charcoal production declines following a peak (boom) because of forest biomass loss, which makes it expensive to continue intensive charcoal production. In the model of a non-timber forest product system in Tanzania, Shaafsma et al. (2014) assume that production is related to time investments and forest product availability. At present, it remains unclear at what forest biomass extent charcoal production decreases exactly and to which levels forest and charcoal biomass drop in open access systems. For instance, it could be that actors in the charcoal system foresee a potential crisis and intervene to prevent a collapse, cause the system to stabilizes at higher levels of charcoal and forest biomass, even at high demand.

### 4.2 System transitions

Our simulations highlight the importance of system transitions to mitigate deforestation and subsequent collapse of charcoal production at high demands. Short-term benefits of communal management depend on the timing of transition, as well as on demand. When transitions occur early and are instantaneous, forests are relatively intact allowing for a fast recovery, while sustaining charcoal production. Transitions after a long time at high demands and low forest biomass levels limit production for hundreds of years until forests regenerate sufficiently to sustain charcoal production. These results suggest that communal management should be introduced early and instantly in areas with high forest biomass to foster continuation of charcoal production on a short term. Evidence suggests that communal management reduces forest degradation (Ameha *et al* 2014), raises awareness (Gobeze *et al* 2009) and empowers communities (Ostrom 2009), although it is prone to corruption (Poteete and Ribot 2011).

Transition towards private systems with plantations allow for higher charcoal production and a full recovery of the forest even upon a gradual transition. This scenario requires that our assumption of pre-existing ready-for-harvest plantations for charcoal at the time of a transition is met. An example of an area in which private forest plantations for charcoal production have been implemented successfully is Brazil, where 64.4% of charcoal is produced from planted forest (Sonter *et al* 2015). Besides this, evidence suggests that privatization may combat deforestation (Koyuncu and Yilmaz 2013). However, at present, many tropical countries do not have the plantation area needed to meet demands nor the financial means to implement plantations at a large scale (FAO 2017). Further, we assume that plantations are developed outside forested areas. Some authors have argued that private plantations could replace natural forests as the main supply of feedstock for charcoal production (Azar and Larson 2000, Piketty *et al* 2009, Sonter *et al* 2015) but whether this actually occurs needs to be assessed. In general, 1.5 million ha of forest per year are converted to plantations (e.g. including oil palm plantations) and the majority of studies report lower invertebrate, bird and mammal diversities in plantation forests compared to other land uses (Stephens and Wagner 2007).

### 4.3 Charcoal production efficiency

Promoting charcoal production efficiency in open access systems mitigates the impact of intermediate demands on forest biomass by introducing charcoal kilns with efficiencies between 40% to 60%. These results are in line with empirical research that shows the positive effect of efficient kilns on forest levels (Mwampamba 2007). However, at high levels of demand, increasing charcoal production efficiency does not mitigate a system collapse, suggesting that promoting production efficiency is only effective at low and intermediate demand. This suggest that at high demand, a combination of interventions is necessary, such as combining increased production efficiency with communal management, private systems, or reductions in demand.

### 4.4 Changes in demand

Impacts of gradual annual increases in demand only becomes visible at the long term (after 200+ years) at low and medium initial demand levels, in particular for forest biomass. Their gradual impact indicates that no early warning signals occur upon an annual rise in demand and that measures can best be taken before forest biomass levels start to decline. Transitions to private and communal management systems may buffer impacts of annual demand increases on forest and charcoal biomass.

At high demand, large annual reductions are necessary to support forest regeneration; otherwise, forest recovery may take hundreds of years. This is not surprising given that full forest recovery requires at least 100 years under natural conditions without accounting for forest biomass reductions through harvesting (Hofstad 1997, Bonner *et al* 2013, Brown and Lugo 1984). This suggests that interventions to reduce demand alone should be implemented in regions with high forest biomass as these regions have sufficient biomass to allow for quick forest regeneration. In regions with intermediate to low forest biomass, demand-reducing interventions should be combined with interventions that increase production efficiency and/or communal management (at intermediate forest levels) or private systems (at low forest levels). Interventions that reduce demand involve promotion of alternative fuels, such as gas (Kojima 2011, Broto *et al* 2018), as well as the introduction of efficient cooking stoves (Mwampamba *et al* 2013, Dagnachew *et al* 2020). Efforts to reduce demand may require large financial investments, which can cause fiscal burdens (Laan *et al* 2010, Kojima 2011) and rebound effects (Mwampamba *et al* 2013).

### 4.5 Lessons learned

Social-ecological models like the one we present herein are useful to examine the way humans feedback with natural resources and the effects of policy interventions that reduce demand (e.g. by providing subsidies to promote access to alternative fuels, such as gas or solar), increase efficiency (e.g. efficient charcoal kilns) or transition the system (e.g. from open access to communal or private management) on these relationships. However, model results need to be interpreted with caution and should be complemented and validated with empirical work. We find that our model is sensitive to forest carrying capacity, indicating the importance of carefully determining forest carrying capacity upon policy implementations. This finding has implications for policy makers, as transitions to communal or private systems may be less effective in forests with stronger constraints on carrying capacity, such as tropical dry forests. In addition, events that lower forest carrying capacity (e.g. seasonal fires, droughts or logging for timber) may significant increase the impact of charcoal production on forest biomass. In this study a relatively high carrying capacity has been used, approximately equivalent to the average carrying capacity of tropical rainforests (***Supplementary Materials A***; (IPCC 2019)). Therefore the dynamics reflected in this study are on the optimistic side for tropical forest with lower carrying capacities, e.g. tropical dry forests.

Overall, we kept our model relatively simple, excluding additional factors known to affect charcoal production, such as conflict, corruption, export and climate change (FAO 2017). Further, we examined transitions in three systems from open to private, but we are aware that numerous charcoal production systems may occur in the same area, may interact with each other, and/or feedback with other systems, like agricultural systems (Iiyama *et al* 2017, Mwampamba 2018). Finally, social-ecological charcoal systems are dynamic across time, space and geographies (FAO 2017). Charcoal producers and consumers behave differently across regions, have variable forest practices and production strategies (FAO 2017). Additionally, consumption patterns may change due to a range of cultural, political, environmental and social factors (FAO 2017). Nonetheless, by focusing on main drivers, our model provides a fundamental understanding of the general dynamics of charcoal systems, which can be extended in the future to reflect local dynamics.

### 4.6 Conclusions

Charcoal is one of the controversial biomass-based renewable energies, produced in complex social-ecological systems around the world (FAO 2017). We assess the conditions under which transitions to sustainable charcoal systems for forest and charcoal-supported livelihoods take place. We find that single strategies are sufficient at low demand, but that more complex and multilayered strategies are required at high demand, for instance through transitions from open access to communal management or private systems in combination with interventions that improve production efficiency and reduce demand. Our modelling exercise suggests that transitions to sustainable charcoal production may even be possible at high levels of demand, provided that a mix of strategies are implemented that take into account present forest biomass levels, forest carrying capacity and the experienced demand.

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## Author contributions

The author contributions are based on CRediT (Contributor Roles Taxonomy), which aims to recognize individual author contributions to facilitate collaborations and to diminish disputes among authors (https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement).

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# Chapter 4

## Detecting charcoal production sites using a combined remote sensing approach with Landsat-8, Sentinel-2 and VHR data

**Authors**
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*This chapter is under review in the journal Remote Sensing of Environment*

The theoretical modelling exercise of **Chapter 3** paves the way for **Chapter 4** and **Chapter 5** of this thesis, in which I empirically assess impacts of charcoal production on tropical forest spatial arrangement in different charcoal production systems. Where in **Chapter 3** impacts of transitions in charcoal production systems on forest biomass dynamics were modelled non-spatially in a theoretical modelling environment, in **Chapter 4** and **Chapter 5** forests use for charcoal production is empirically assessed. Rather than analyzing a direct transition in charcoal production system, charcoal production sites in two charcoal production systems are compared to each other, providing a proxy for potential effects of charcoal production system transitions.

In **Chapter 4**, I develop a combined remote sensing approach for charcoal production site recognition based on Landsat-8 and Sentinel-2 classification and inspection of Very High Resolution Imagery (VHR). Hereby, I primarily look at resource units (i.e., forest cover) that are used for charcoal production in a resource system of six Tanzanian villages under two governance regimes: three villages under open access and three villages under community-based natural resource management (CBNRM). Ultimately, the final ensemble maps produced in **Chapter 4** may inform the monitoring of charcoal sites and the assessments of drivers behind forest use.

**Figure 4.1** provides an overview of the social-ecological system components assessed in **Chapter 4**, their interactions, and the specific charcoal production systems compared. The **Supplementary Materials** of **Chapter 4** can be found in the **Appendix of Chapter 4** of this thesis.

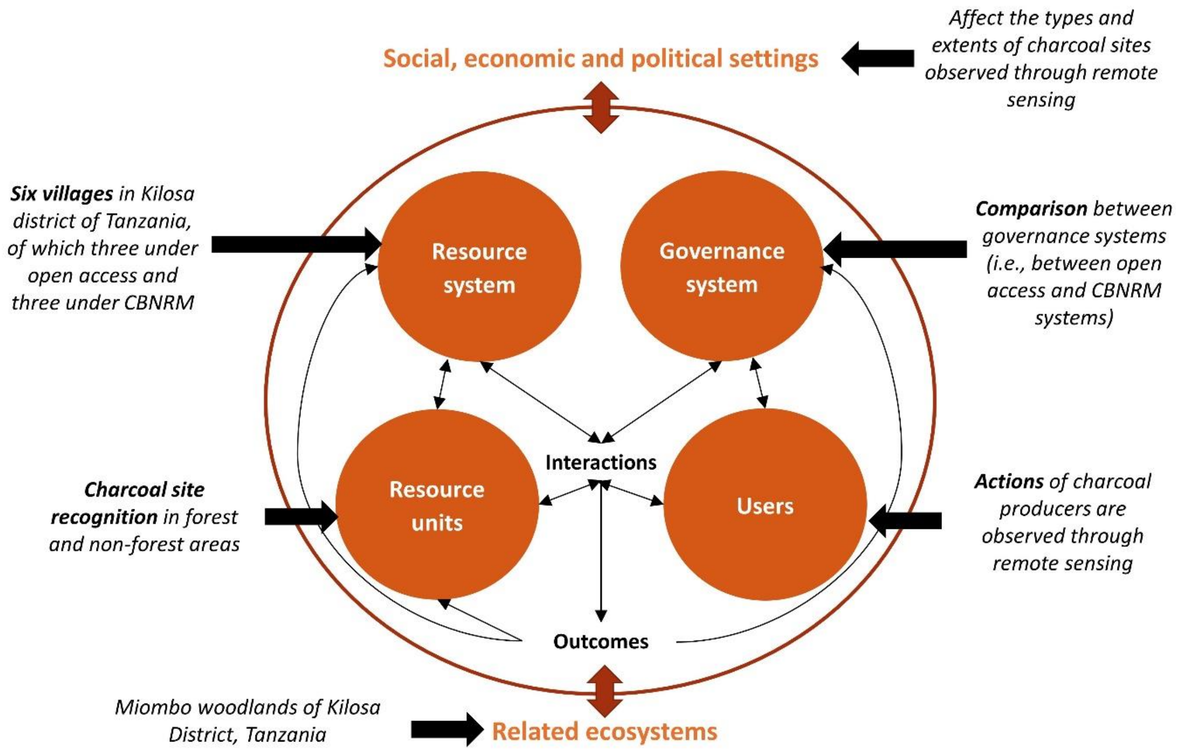

**Figure 4.1.** The social-ecological system components assessed in **Chapter 4**, their interactions, and the specific charcoal production systems compared. CBNRM = community-based natural resources management.

Scientific paper under review

# Detecting charcoal production sites using a combined remote sensing approach with Landsat-8, Sentinel-2 and VHR data

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## Abstract

Biomass-based renewable energies provide energy and income for millions of people but its production causes forest loss, degradation and carbon emissions. Charcoal production alone contributes to 7% of global deforestation, predicted to increase 5% by 2100. Charcoal production sites remain difficult to detect through remote sensing because they contain multiple features that (i) vary in size and material (i.e., kiln scars, surrounding bare soil, and harvesting areas), (ii) are scattered and over-time disintegrate into the landscape, and (iii) may be covered by tree canopy. We develop an approach that combines two random forest algorithms for charcoal site classification, trained with Landsat-8 and Sentinel-2 data, and one visual imagery inspection method to identify kilns/kiln scars on Very High Resolution (VHR) Worldview-2, and Planet data, applied over a 405.70 km$^2$ study site in Tanzanian miombo forests. To classify charcoal sites, we trained random forest classifiers with 30 random training data sets of charcoal, forest and non-forest locations for Landsat-8 time series and one Sentinel-2 image. We obtained high accuracy for both Landsat-8 and Sentinel-2 classifications (Landsat-8: 82.27 ± 2.40% and Sentinel-2: 83.56 ± 2.82%). The most important input variables for Landsat-8 were Band 3 (Green) and 4 (Red), likely attributed to greening-up of regenerating harvesting areas, and Band 3 (Green) and Normalized Burn Ratio (NBR) for Sentinel-2, likely attributed to a combination of heat-stress and forest vegetation age. We used both sets of 30 classification maps to (i) create two ensemble maps with pixels classified as charcoal site 100% of the time, and (ii) calculate two Shannon entropy maps showing per-pixel uncertainty. We combined this output to derive a classification robustness map, which provides a per pixel estimate of the likelihood that a classified pixel is a charcoal site. On this map, we distinguished charcoal sites with minimum prediction uncertainty (i.e., maximum classification robustness). Finally, we overlaid the classification robustness map with 3,015 visually detected kiln scar locations, and distinguished 237 (0.21 km$^2$) high robustness (i.e., maximum classification robustness and detection of kilns), 22,281 (20.05 km$^2$) medium robustness (i.e., maximum classification robustness or identified kiln scars overlaying lower classification robustness sites), and 88,930 (80.04 km$^2$) low robustness 30 m pixels detected as charcoal sites (i.e., low classification robustness or visually identified kiln scars only). We observed higher robustness in clear cutting areas than in canopy covered areas, related to an inability to visually identify kiln scars, similarities between signals from canopy covered harvesting sites and undisturbed forest, and smaller harvesting areas. Yet, we for the first time show that combining information of varying spatial resolutions enhances robustness of charcoal site detection, allowing for improved monitoring of charcoal production and its forest and ecosystem services implications.

*Keywords*: Charcoal, Random Forest, Landsat, Sentinel, Very High Resolution Imagery

## Highlights

- We developed a combined charcoal site detection method with Landsat-8, Sentinel-2 and VHR data.
- Random forest models for Landsat-8 and Sentinel-2 achieved high accuracy (82.27 and 83.56 %).
- Combining classification and inspection methods improves charcoal site detection robustness.
- Different resolution satellite data detect varying features (kiln (area) and harvesting area).
- Charcoal site detection is influenced by spatial and temporal resolution, and canopy cover.

## 1. Introduction

Globally, deforestation and forest degradation affects ecosystems and their services (Curtis *et al* 2018, Sloan and Sayer 2015). Charcoal production contributes to up to an estimated 7% of global deforestation annually, as well as to forest degradation (Chidumayo and Gumbo, 2013), causing a loss of biodiversity, carbon stocks, soil stability and other forest-related ecosystem services (Chidumayo and Gumbo, 2013; Woollen, et al. 2016). A 5% increase in charcoal demand is predicted by the year 2100 driven by urban population growth and global demands for biomass-based energy (Santos et al., 2017), which will likely result in additional deforestation and carbon emissions (Bailis et al., 2015; Santos et al., 2017; Specht et al., 2015). To understand impacts of charcoal production on forests, we need better estimates of the spatial extent of deforestation related to charcoal production (Mwampamba 2007, Mwampamba *et al* 2013). We also need to distinguish between drivers of charcoal production by differentiating between charcoal as by-product of agricultural expansion (Iiyama *et al* 2017), and charcoal as final product to meet energy demands (Ahrends *et al* 2010). To our knowledge, charcoal production sites have only been examined in a small set of regions (Sedano *et al* 2016), and charcoal production remains difficult to detect for the majority of regions, challenging the spatial assessment and monitoring of the contribution of charcoal production to deforestation and its effects on forest dynamics and biodiversity (Bolognesi *et al* 2015, Sedano *et al* 2016).

Detecting charcoal production through remote sensing is challenging because charcoal sites contain multiple features, which vary in size and material. First, charcoal is produced from forest biomass, which is either harvested through selective cutting (Kouami et al., 2009; Woollen et al., 2016) or through clear cutting (Iiyama et al., 2017). Selective cutting entails the selection of trees within a harvesting area based on criteria (e.g., diameter at breast height, species type, location) based on tree species preference (Malimbwi and Zahabu 2008, Ndegwa *et al* 2018) and/or pre-defined in a harvesting plan (Ishengoma et al., 2016). As a result, charcoal production appears scattered throughout the landscape (FAO, 2017), making it difficult to detect selectively cut charcoal sites through remote sensing. In contrast, clear cutting results in the removal of all trees in a forested area (e.g., for agricultural expansion) (Iiyama *et al* 2017), leaving behind larger and more regularly distributed charcoal sites. Selectively cut and clear cut charcoal sites may be scattered throughout the same landscape, causing a mosaic of charcoal sites with varying forest biomass availability, biodiversity and canopy cover (Sedano *et al* 2020b). Second, charcoal kilns (i.e., carbonization ovens), are relatively small in size but their shapes vary substantially across regions (Bailis *et al* 2013, Kammen and Lew 2005), and with the level of experience of charcoal makers (Schure *et al* 2019). For example, Sedano et al. (2016) found kilns of 8.1 m ± 4.6 m in length and 2.2 m ± 0.3 m in width in the Tete province of Mozambique (Sedano *et al* 2016). These varying dimensions make it difficult to detect kilns on imagery with a spatial resolution greater than 20 m (Nakalema 2019). Third, kilns leave scars on the land (i.e., burnt soil and small leftover charcoal pieces) surrounded by bare soil, which are either located underneath forest canopy (e.g., upon selective cutting) or on bare soil (e.g., upon clear cutting) (Sedano et al., 2016). Therefore, different types of data and methods are required to detect all different components of charcoal sites (i.e., kiln(s), kiln scar(s), surrounding bare soil, and harvesting areas) to accurately map and monitor charcoal production under varying cutting and production practices (Sedano et al., 2016, 2020b).

Remote sensing has contributed with varied success to the detection, mapping and monitoring of charcoal production and its impact on forest extent and degradation. Previous studies have employed a range of methods to detect charcoal kilns/kiln scars, including visual imagery inspection (Sedano et al., 2016) and object-based semi-automated detection (Bolognesi et al., 2015). For example, Sedano et al. (2016) used visual imagery inspection to distinguish charcoal kilns/kiln scars on Worldview-2 Very

High Resolution (VHR) imagery over Mozambique. The authors located 8561 kilns/kiln scars and, although detection accuracies were not mentioned, kiln (scar) appearance varied depending on the age of the kiln (scar), soil contrast, image acquisition date, viewing and illumination angles, and atmospheric conditions. In a follow up study, the authors used a region growing (RG) segmentation approach (i.e., segmentation of imagery based on the examination of neighboring pixels of initial seed points) to identify kilns/kiln scars in the same area on VHR imagery, with as input a single band (NIR default) or the Normalized Difference Vegetation Index (NDVI) in the rainy season (Sedano *et al* 2021). Through this approach, they were able to expand the time range of their study to 7 years and provide accuracy assessments based on the overlap between RG outputs and visually inspected kilns/kiln scars, which ranged between 98.15 and 100%. They found an average area subjected to charcoal production of 203 km$^2$ per year in their study site, from which 1,081,000 ± 2461 Mg biomass was removed (Sedano *et al* 2021). Bolognesi et al. (2015) used object-based segmentation on Worldview-2 data to detect charcoal sites in Somalia with accuracies ranging from 60 to 90%. Lower accuracies were due to an inability to detect smaller kilns/kiln scars, kilns/kiln scars with irregular shapes, and canopy shade effects (Bolognesi et al., 2015). Nakalema (2019) developed a change-in-difference-index method, using Sentinel-2 data to detect charcoal sites in Somalia with variable accuracy. Other studies focused on charcoal related deforestation and forest degradation using time series analyses (Dons *et al* 2015, Nakalema 2019, Sedano *et al* 2020a, Wurster 2009). For example, Sedano et al. (2020a,b) assessed whether forest degradation through charcoal production could be identified, using NDVI phenological curves derived from Sentinel-2 and Landsat-8 data. The authors showed that NDVI phenological curves indicate change points in forest productivity attributable to charcoal production, as intense tree regeneration after charcoal production commonly results in a rapid recovery of the spectral signal to pre-disturbance values within a year (Sedano et al., 2020a, 2020b). Although these methods show promising results, they have not yet been applied concurrently in the same area to examine the performance of different data sources with varying spatial and spectral resolutions, in particular to understand the need for VHR imagery, as it has variable availability and accessibility over the vast areas where charcoal is produced in Sub-Saharan Africa. These studies suggest that no single method may suffice to fully detect charcoal production, and that it is important to understand how methods that detect different features of charcoal production sites may complement each other to obtain more robust assessments of charcoal production. Besides this, they indicate the need to test method performance along a gradient of forest cover.

In this study, we develop a combined remote sensing approach to detect, map and monitor charcoal production in miombo woodland ecosystems of Tanzania, where individual or small groups of charcoal producers derive charcoal through a conventional construction process, during which layered wood is covered with soil and grasses to form a kiln in which the wood is carbonized (Schenkel *et al* 1998). More specifically, we (i) develop two automated methods for charcoal production site classification, using Landsat-8 and Sentinel-2 data, (ii) use visual inspection for charcoal kiln (scar) detection on VHR Worldview-2 and Planet imagery, (iii) compare the performance of the methods along a gradient of forest cover, and (iv) derive a robustness metric based on the combination of the two automated and one visual inspection method, in order to distinguish areas that are more likely to be charcoal sites from areas that are less likely to be charcoal sites. We hypothesize, that the method based on Landsat-8 takes advantage of the phenology of harvesting areas, while we expect that the method based on Sentinel-2 takes advantage of the higher spatial and spectral resolutions (in comparison to Landsat-8) to detect kiln scars and surrounding bare soil. Finally, we expect that the visual inspection of VHR data enables detection of kilns/kiln scars (Sedano et al., 2016). Our study provides a first combined remote sensing approach to detect charcoal production in an area subjected to a diversity of harvesting regimes, taking advantage of the varying spatial, temporal and spectral resolutions of satellite imagery to detect all charcoal site features (i.e., kilns/kiln scars, surrounding bare soil, and harvesting area).

## 2. Methodology

### *2.1. Study system*

This study was conducted in Kilosa district, approximately 400 km west of Dar-es-Salaam city in eastern Tanzania (Fig. 1). The area is characterized by tropical dry forests, primarily Miombo woodlands, which are dominated by: *Brachystegia bohemii*, *Brachystegia spiciformis*, *Brachystegia microphylla*, *Combretum* species, *Albizia* spp., and *Commiphora* spp. (Ishengoma et al., 2016). In the area, elevation ranges from 400 to 2200 m and temperature ranges between 19 and 30 °C with an average of 25 °C (Ishengoma et al., 2016). Precipitation ranges between 800 and 1200 mm annually (up to 1600 mm in mountainous regions), and its distribution is bi-modal with a short rainy season between November and January and a longer rainy season between March and May, with a peak in April (Ishengoma et al., 2016).

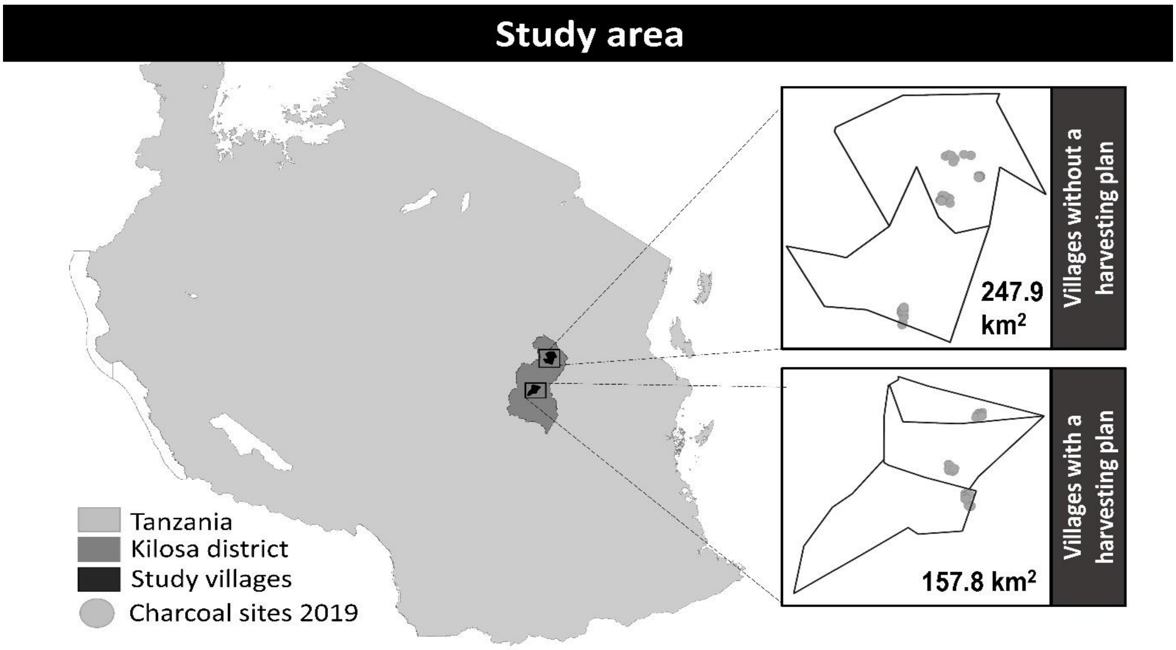

**Figure 1.** The study area; six villages in the Kilosa district of Tanzania. Three villages have a harvesting plan for the use of their village forest resources. The other three villages do not have a harvesting plan in place. At present, the village boundary of one village without a harvesting plan is unclear because it only recently acquired the status of village by the Tanzanian Government. We conducted the remote sensing analyses within the extents of the two village types.

Our study area included six villages, which in total cover an area of 405.70 km$^2$ (Fig. 1). The villages were selected to represent different management regimes, charcoal production intensities, and different types and extents of forest cover. Three villages take part in the Transforming Tanzania's Charcoal Sector (TTCS) project of Tanzania Forest Conservation Group (TFCG), which implements community-based natural resources management (CBNRM) of charcoal production (Ishengoma et al., 2016). In these villages, wood for charcoal production was extracted through selective cutting, under which wood harvesting was restricted to alternating harvesting blocks of 50 m located at least 60 m away from a water body following a checker-board pattern (Ishengoma et al., 2016). In these 50 m blocks, charcoal producers were allowed to harvest non-timber tree species with dbh > 15 cm (for details of the harvesting plan see Ishengoma et al. (2016)). We refer to the three villages that take part in the TTCS project as *villages with a harvesting plan*. Together villages with a harvesting plan cover an area of 157.80 km$^2$. As the existing harvesting plan promotes selective cutting, canopy cover often remains present in charcoal sites of villages with a harvesting plan. The other three villages in our study area did not take part in the TTCS project and charcoal production was mainly carried out illegally in these villages. Therefore, these villages serve as a 'control', and we refer to them as *villages without a harvesting plan*. Together villages without a harvesting plan cover an area of 247.90 km$^2$ and we observed a mix of large clear-cutting areas and areas subjected to selective cutting in the area. *Ad-hoc* information by members of TFCG, the District Council, and the Village Councils of all study villages, as well as scientists from Sokoine University of Agriculture (SUA) confirmed that deforestation and forest degradation in our study area can mainly be attributed to charcoal production, often as a by-product of land clearance for agriculture.

### *2.2. Training and test data*

We obtained charcoal site data in the field. We defined a charcoal site as the kiln(s) and/or their scar(s), the surrounding bare soil, and the surrounding harvesting area. Harvesting areas were defined as the area encompassing all trees that were cut to produce charcoal in kiln(s). In one harvesting area multiple kilns/kiln scars could be present.

We conducted a one-month field survey in August 2019 to collect data on the location and characteristics of 184 charcoal sites over the six villages in our study area. The 184 charcoal sites were evenly distributed over the study villages with and without a harvesting plan (92 sites each). We obtained consent from the village leaders to sample charcoal sites within their village boundaries, and we were guided to charcoal sites by local charcoal producers and/or members of the village natural resource committee or Village Council. We determined the geographical coordinates of each charcoal site, using a GPS (Garmin eTrex®), accuracy of ± 5-10m) (Garmin 2020) by standing in the middle of the kiln or its scar. The ± 5-10 m GPS accuracy may have caused spatial mismatches between the actual locations of the kiln (scar) and GPS coordinates. Besides this, we measured the length, width and (when possible) height of the kiln (scar), and used this information to assess whether these kiln (scar) characteristics influence its detectability. We also determined the perimeter of the respective harvesting area by delimiting its polygon with the GPS instrument under the guidance of charcoal producers and/or members of the local village natural resource committee or Village Council. We examined the effect of the perimeter of the harvesting area on charcoal site detectability.

We augmented the field data with equal numbers of locations for forest and non-forest land (i.e., agriculture, buildings and bare soil), which we visually interpreted from Worldview-2 data for the year 2017, derived through the third-party program of ESA. Visual inspection of VHR satellite imagery is common practice for the identification of validation points (Zhang et al., 2021). For the year 2019 data was available in Google Earth in one of the villages without a harvesting plan (Google Earth 2019). These locations were used as training data for the random forest algorithms (see Section 2.4). Thus, following fieldwork and visual inspection of VHR imagery, we had the following data for three classes: (i) charcoal sites (n = 184), (ii) forest sites (n = 184), and (iii) non-forest sites (n = 184).

### *2.3. Remote sensing data*

In this study, we tested the ability of four satellite data types, varying in spatial, temporal and spectral resolution, to detect charcoal sites. We used (i) Landsat-8 (7 bands, 30 m), (ii) Sentinel-2 (9 bands, 20 m), (iii) Worldview-2 (4 bands, 2-0.6 m), and (iv) Planet (4 bands, 0.5 m) (Table 1). Because Landsat-8 and Sentinel-2 data have different spatial and spectral resolutions, we expected these imagery to provide different spectral information on charcoal sites, namely the harvesting area in case of Landsat-8, the kiln(s), kiln scar(s), and surrounding bare soil for Sentinel-2, and the kiln/kiln scar for VHR Worldview-2 and Planet data (Table 1). Therefore, we expected that combining methods with Landsat-8, Sentinel-2, and VHR data inputs exploit all different characteristics of charcoal sites, rather than only one aspect, and that it would provide us with an opportunity to reduce variation in charcoal production site identification. We used Landsat-8 data because its spatial and temporal resolutions allow for the detection of the harvesting area through an assessment of its phenology (Sedano et al., 2020). Landsat-8 data has a good coverage of Tanzania at 16-day intervals, providing a dense time series fully available for free (Wulder et al., 2016). Prior studies demonstrated that temporal variation can improve charcoal site detection based on Landsat-8 data (Sedano *et al* 2020b, 2020a) because NDVI phenological curves indicate charcoal production induced change points in forest productivity over 1 year. We used Sentinel-2 data because it provides higher spatial and spectral resolutions than Landsat-8, and because it performed well in automated detection of kiln scars in a prior study (Nakalema 2019). We used VHR Worldview-2 and Planet data because it allows for the visual detection of charcoal kilns and their scars (Sedano et al., 2016); a method that cannot be applied to lower spatial resolution Landsat-8 and Sentinel-2 data. We obtained Worldview-2 and Planet data for dates as close as possible to the field data collection dates to validate our approach. For Planet data, we planned the acquisition for 2020 because we wished to repeat field sampling of charcoal sites in this year, but we were unable to carry out this fieldwork due to the COVID-19 pandemic. Nonetheless, this imagery allowed us to test the detectability of 2019 charcoal kiln scars in our study area.

**Table 1.** Description of sensor types, images used, bands and spatial resolution, and the features they are expected to detect based on their spatial and spectral resolution.

| Sensors/satellites | Year | Number of Images | Bands | Resolution (m) | Feature |
|---|---|---|---|---|---|
| **Landsat 8-OLI** | 2019 | 19 | 7 | 30 | Harvesting area |
| **Sentinel-2** | 2019 | 1 | 9 | 20 * | Kiln, kiln scar, and surrounding bare soil |
| **WorldView-2** | 2017 | 2 | 3 | 0.6 | Kiln and kiln scar |
| **WorldView-2**** | 2019 | ** | RGB | 2 | Kiln and kiln scar |
| **Planet** | 2020 | 1 | 3 | 0.5 | Kiln and kiln scar |

* All 10 m resolution bands were converted to 20 m resolution.
** Imagery visualized and inspected in Google Earth

### *2.3.1 Landsat-8 OLI*

We downloaded all Landsat-8 OLI Level 2 data for the year 2019 for our study area (a total of 19 images at 16 day intervals were available, approximately two per month) (see Appendix Table A1 for the image acquisition dates) from the United States Geologic Survey (USGS) Earth Explorer platform (https://earthexplorer.usgs.gov/). This data was already atmospherically corrected to surface reflectance, and georeferenced to UTM/WGS84 projection (USGS, 2019). Details about atmospheric correction are included in the Land Surface Reflectance Product Guide (USGS, 2020). Therefore, no extra pre-processing steps were required to conduct temporal analyses (Young et al., 2017). Our entire study area was covered by 1 tile of 185 x 180 km$^2$, and we used all the 19 images and the 7 bands in our analyses (Table 1). We used the CFMask (i.e., a cloud, cirrus, water and snow mask), readily provided with preprocessed Landsat-8 data, to mask out clouds by excluding pixels with high, medium and low confidence clouds, high confidence cirrus, water and cloud shadows (USGS, 2020). We used all 19 Landsat-8 images, irrespectively of the percentage of removed cloud cover in the image, to include as much data as possible because this allows for the best possible approximation of land surface phenology (Gumma *et al* 2020, Oliphant *et al* 2019). All downloaded Landsat-8 surface reflectance data was multiplied by 10,000 for calculation and display purposes (USGS 2020).

### *2.3.2 Sentinel-2*

We downloaded Sentinel-2 data using the Copernicus Open Access Hub (https://scihub.copernicus.eu/). The available Sentinel-2 data was georeferenced in UTM/WGS84 projection. Our study area was covered by one Sentinel-2 tile of 100 x 100 km$^2$, and we used only one image date (12th of August 2019). We chose the image date by eliminating tiles with > 40% cloud cover, and picked the image closest to the period of our field campaign and with most pixels overlapping the charcoal site locations observed in the field (see Appendix Fig. A1 for an overview of the cloud cover on the Sentinel-2 image). In total, 64.1 km$^2$ of our study area of 405.7 km$^2$ was covered in clouds on the Sentinel-2 image used in this study, of which 6.6 km$^2$ was located in villages without a harvesting plan and 57.5 km$^2$ in villages with a harvesting plan. We used all 9 Sentinel-2 bands in our analyses (Table 1). Almost the entire study area was covered by the Sentinel-2 tile, covering an area of 403.4 km$^2$ out of 405.7 km$^2$ (see Appendix Fig. A1 for the extent to which the study area was covered). Bands with a spatial resolution of 10 m were aggregated to 20 m resolution using the nearest neighbor algorithm. We chose to classify at 20 m resolution because it allowed us to obtain reflectance input data at consistent spatial resolution. As charcoal kilns/ kiln scars vary substantially in size and width, we believe that consistency in spatial resolution across random forest inputs is warranted. Finally, we expect a higher likelihood that one kiln/kiln scar is completely covered by a 20 m than a 10 m Sentinel-2 pixel.

The pre-processing of Sentinel-2 data consisted of two steps: (i) atmospheric correction and (ii) cloud masking. First, we converted level-C1 (top-of-the atmosphere reflectance) Sentinel-2 data to level-2A (bottom-of-the atmosphere reflectance) data, using the 'sen2corr' v2.8 processor (Main-Knorn et al., 2017). The parameters for atmospheric correction through 'sen2corr' are provided in the Sen2Cor Configuration and User Manual (Mueller-Wilm *et al* 2019). Second, we masked out pixel values corresponding to medium and high probability clouds, cloud shadow, thin cirrus and unclassified pixels, using the 20 m resolution scene classification file (SC file) (Main-Knorn et al., 2017). Sentinel-2 level-2A surface reflectance data was multiplied by 10,000 for purposes of display (Main-Knorn *et al* 2017).

### *2.3.3 Worldview-2, Planet data and CNES Airbus data*

We obtained one Worldview-2 image (standard (2A) / ortho ready standard (OR2A) © Maxar Technologies (2017) provided by European Space Imaging) for each set of villages for 2017 through the Third-Party Data program of the European Space Agency (ESA; https://earth.esa.int/web/guest/pi-community/apply-for-data/3rd-party (accessed 20th of December 2020)). We selected the year 2017 because (i) it was the closest available year to 2019 that provided data for our entire study area, (ii) it was acquired around the same time, and (iii) cloud cover was less than 4% for the entire imagery. Worldview-2 image dates were 18th September 2017 for villages without a harvesting plan, and 10th August 2017 for villages with a harvesting plan. Therefore, the acquisition date of the acquired Worldview-2 data for the year 2017 approximately matched the timing of our field study in August 2019. Details on the images can be explored on the Digital Globe Discovery page (https://discover.digitalglobe.com/); image IDs are 1040010033B2F600 for villages with a harvesting plan and 103001006E5B7F00 for villages without a harvesting plan. Besides this, we visually inspected the VHR data from the Airbus Earth Observation Satellite Imagery Service of the French Space Agency (CNES), available in Google Earth, which only covered one village without a harvesting plan for the 19th of March 2019.

We purchased five targeted acquisitions of Planet data from Planet Labs for our study area (Team Planet 2017), collected between June and October 2020. The data was acquired on the 30th August 2020, 04th October 2020, and 10th October 2020 and only covered part of our study area. Therefore, the acquisition windows of the purchased Planet data of 2020 approximately matched the timing of our field study in August 2019. We acquired Planet imagery for the year 2020 because we planned to revisit the study area in this year. Unfortunately, our visit was cancelled due to COVID-19. Nonetheless, we still chose to use the 2020 Planet data in this study because it complements the Worldview-2 data of 2017, as it gives an indication of the visibility of charcoal sites of 2017/2019 on VHR imagery of 2020. The visual inspection of Planet data also allowed us to assess the suitability of Planet imagery for charcoal site identification through visual imagery inspection, which is particularly important as Planet data is becoming more ubiquitous and freely accessible.

Both Planet (https://developers.planet.com/docs/data/planetscope/ (accessed 24th of August 20201)) and Worldview-2 data (© Maxar Technologies (2017), provided by European Space Imaging), were atmospherically corrected by the distributor.

### *2.4 Method I: Charcoal site classification with Landsat-8 and Sentinel-2*

We developed two classification methods to classify charcoal sites: one for Landsat-8 and one for Sentinel-2 data. We developed a separate procedure and workflow for Landsat-8 and for Sentinel-2 data, as detailed in Fig. 2 and Fig. 3, respectively. We used the random forest (RF) algorithm (Cutler et al., 2012) to classify the data into three classes (i) charcoal sites, (ii) forest sites, and (iii) non-forest sites. We chose the Breiman's RF algorithm for classification and regression (Breiman *et al* 2018). The RF algorithm is an ensemble classifier, which builds multiple decision trees to obtain a 'forest' that best predicts user defined classes (in our case charcoal, forest and non-forest sites) (Belgiu and Drăgu 2016). Random forest algorithms have a couple of advantages over other machine learning classifiers. First, the RF classifier is a non-parametric method that does not rely on assumptions of normality (Belgiu and Drăgu 2016). Second, the RF classifier has a higher performance than decision tree classifiers (Ghimire *et al* 2012), Linear Discriminant Analysis (LDA) (Shang and Chisholm 2014), the Binary Hierarchical Classifier (BHC) (Ham *et al* 2005), and Artificial Neural Network classifiers (Chan and Paelinckx 2008), upon comparison of their classification accuracies (Belgiu and Drăgu 2016). Further, the RF classifier often achieves better and otherwise comparable results to alternative ensemble classifiers, such as AdaBoost (Miao *et al* 2012). Third, the RF classifier only requires the user to set two parameters (Ntree – number of trees in the 'forest' and Mtry – number of predictors sampled to split each node), to which the algorithm shows limited sensitivity, and which allows it to handle input data of many variables simultaneously, without penalizing the accuracy due to over-parameterization (Belgiu and Drăgu 2016). Fourth, RF algorithms are user-friendly, have been used successfully in many classification problems (Cutler et al., 2012), and exhibit efficient computation (i.e., take less time than alternative classification approaches) (Belgiu and Drăgu 2016). This was important, as we wished to develop a user-friendly combined remote sensing method that can be implemented by scientists, policy-makers and managers with varying backgrounds.

### *2.4.1 Input variables*

We used the surface reflectance data from Landsat-8 level 2 and Sentinel-2 level-2A (Table 1), and selected a set of indices as inputs to the two RF classifiers. We used indices to complement raw reflectance data because a combination of reflectance at different wavelengths in indices corresponds to biophysical properties that cannot be retrieved by raw reflectance data alone (Lamb *et al* 2009).

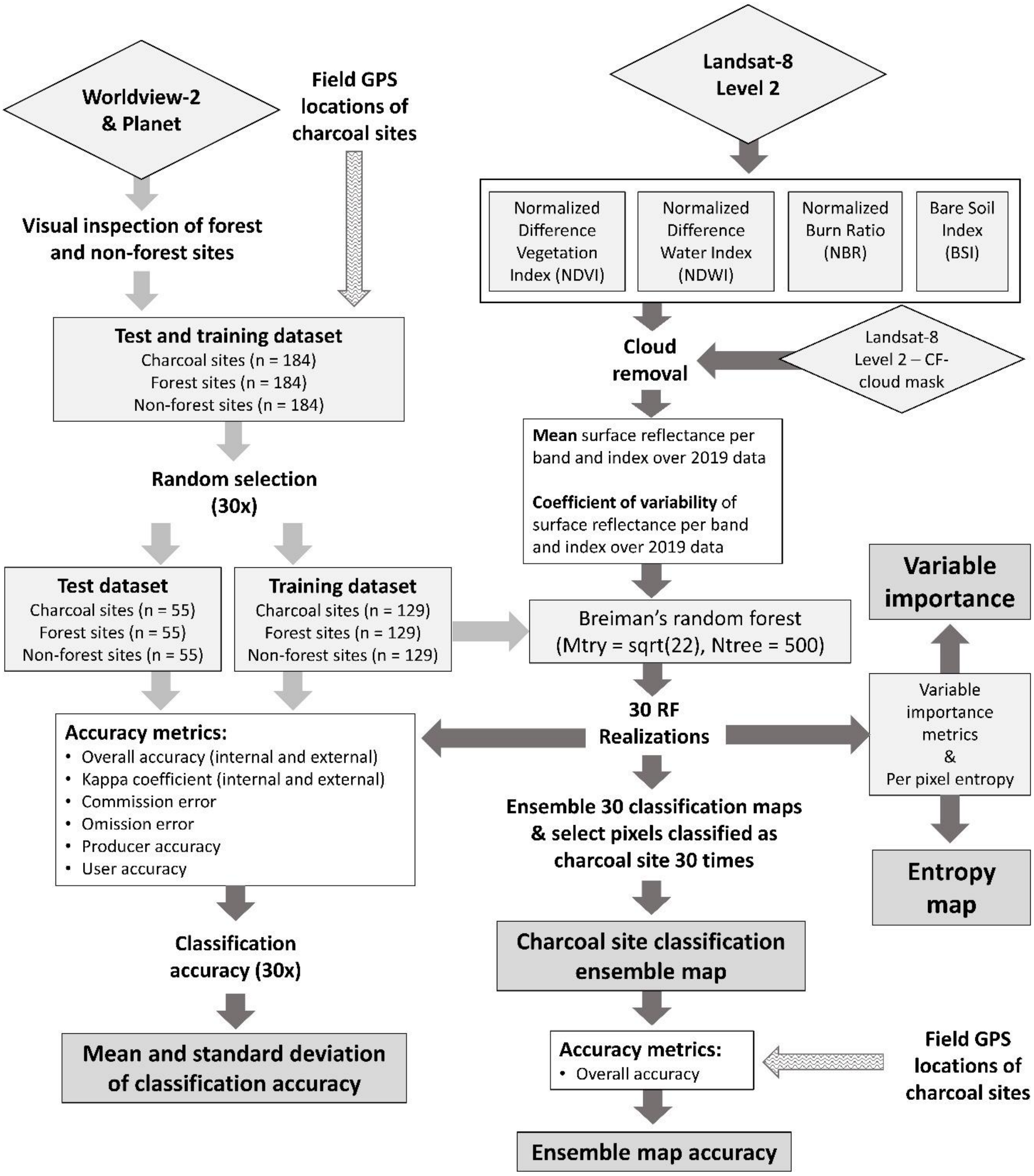

**Figure 2.** Workflow of the automated method classification method developed for Landsat-8 data.

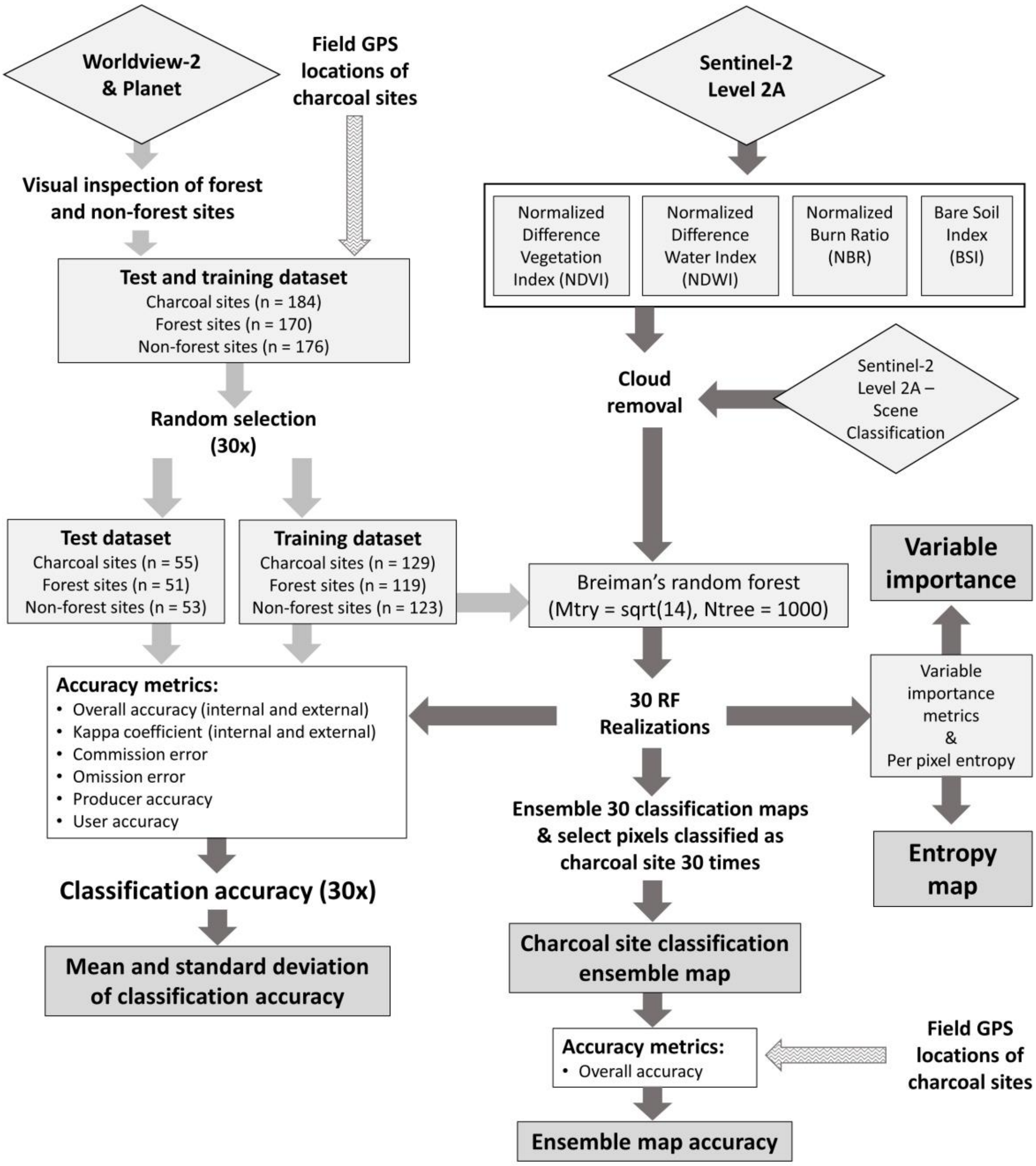

**Figure 3.** Workflow of the automated method classification method developed for Sentinel-2 data.

Indices may also provide normalized data, specifically targeted to small areas of the spectrum (Gao 1996), i.e., they reflect differences between reflectance at specific wavelengths of the electromagnetic spectrum. For example, when computing the Normalized Difference Water Index (NDWI), water features are enhanced (very low NIR values), while terrestrial vegetation and bare soil is suppressed (very high NIR) (McFeeters 1996). Indices have a long tradition in remote sensing to highlight specific properties of materials that are not easily captured by single band approaches (Gao 1996).

In total, we calculated the following indices for both imagery types: NDVI (Tucker 1979), NDWI (Gao, 1996), Bare Soil Index (BSI) (Rasul *et al* 2018), and Normalized Burn Ratio (NBR) (Key and Benson 2005). We chose NDVI because it is sensitive to reductions in green vegetation related to tree cutting (Kalaba *et al* 2013, Williams *et al* 2008), and, therefore, likely supports the detection of harvesting areas of charcoal sites. Thus, we expect that NDVI provides important information for the Landsat-8 classification, as its 30 m pixel size likely targets the harvesting area (see Section 2.3). This expectation is substantiated by three previous studies that use NDVI derived from Landsat-8 imagery to detect harvesting site regeneration (Sedano *et al* 2020a, 2020b, 2021). For example, Sedano et al. (2021) showed characteristic yearly fluctuations in NDVI in charcoal sites. We also observed that the NDVI phenological curve and the spectral signatures of charcoal sites differed from those of forest and non-forest sites for both Landsat-8 and Sentinel-2 data (Appendix Fig. A2 – A4).

We chose NDWI because this index detects leaf water content (Gao 1996, Matsushita *et al* 2005). Charcoal production may reduce canopy water content due to increased temperatures in areas with active kilns (Gómez-Luna *et al* 2009), potentially causing drought stress. These effects may persist after the charcoal combustion process, as drought stress implications can prevail for a long time (Saatchi *et al* 2013). Therefore, we expect that the presence of an active kiln in the vicinity of the canopy, stem and roots of trees will cause water stress signals that may be detected by NDWI. In addition, biomass harvesting for charcoal production likely affects the thermal buffer capacity of mature forests (Lin *et al* 2017, Longo *et al* 2020). We expect that NDWI may inform Sentinel-2 classification, as it could affect vegetation within the surrounding kiln area, as well as inform Landsat-8 classification because the harvesting area may be subjected to heath stress.

We chose BSI because it is sensitive to increased soil fraction (Rasul *et al* 2018). Hence, BSI likely aids in the detection of kiln scars because limited regeneration takes place in these areas, causing the soil to remain exposed (Myonga 2019, Sangeda and Maleko 2018). Therefore, we expect that BSI provides important information for Sentinel-2 classification, as its 20 m pixel size targets the kiln(s)/kiln scar(s) and surrounding bare soil (see Section 2.3).

Finally, we chose NBR because this index detects burned areas (Rasul *et al* 2018), potentially allowing us to detect the burnt scars of charcoal kilns (Bolognesi *et al* 2015, Sedano *et al* 2016). Even though the burnt area is relatively small, it may still produce a signal in reflectance (Nakalema 2019), potentially detectable with Sentinel-2 data (Roy et al., 2006). Nakalema (2019) also indicates that indices that measure soil properties may provide important information on kiln scars.

Although some indices may provide more important information for Landsat-8 classification (e.g., NDVI (Sedano *et al* 2020a)), while others may provide more important information for Sentinel-2 classification (e.g., NBR (Nakalema 2019)), we included the same indices in both the Landsat-8 and Sentinel-2 RF classifiers for consistency. This provided us with information on the charcoal site features Landsat-8 and Sentinel-2 target, and allowed for a better understanding of the effect of spatial resolution on the importance of indices for charcoal site classification. As no study has used classifiers to detect charcoal production activities before, we tested whether the four indices provide important information to the classifier or not.

For our RF analysis with Landsat-8, we used multiple images (19) (see Section 2.3.1) and the indices described above as input variables because prior studies demonstrate that temporal variation can improve detection of charcoal sites (Sedano *et al* 2020b, 2020a), as NDVI phenological curves indicate charcoal production induced change points in forest productivity over one year. We also observed differences in the NDVI phenological curve between charcoal, forest and non-forest sites (Fig. 4a). To capture temporal variations, we used the mean and the coefficient of variation of surface reflectance as input variables for each Landsat-8 band and the mean and coefficient of variation in NDVI, NDWI, BSI and NBR between January and December of 2019 (19 time stamps). Thus, the mean and coefficient of variation in surface reflectance is calculated per band and index over all 19 Landsat-8 acquisitions. We included the coefficient of variation because we expected surface reflectance of charcoal sites to vary more throughout the year than that of forest and non-forest sites due to forest regeneration following charcoal production (Sedano *et al* 2020a, 2020b). Besides this, the coefficient of variation is used in multiple studies to identify areas with high temporal change (Ghulam 2014, Weiss *et al* 2001), such as areas affected by tropical forest degradation (Ghulam 2014). We observed that the spectral signatures of the three classes differed for Landsat-8 data (Fig. 4b).

For our RF analysis with Sentinel-2, we used one image (see Section 2.3.2) and the indices described above as input variables because charcoal kiln scars have been identified successfully on single Sentinel-2 images (Nakalema 2019). The Sentinel-2 image was acquired in the dry season during which miombo woodlands shed their leaves to conserve water (Frost 1996, Vinya *et al* 2018). Hereby, we avoided potential saturation of NDVI in forests, which could have occurred due to densification of the canopy in the rainy season (Ribeiro *et al* 2012). As the spatial resolution of Sentinel-2 data is higher than that of Landsat-8 (20 m in comparison to 30 m), it approximately matches charcoal kiln(s)/kiln scar(s) and the surrounding bare soil covered by charcoal remnants (Nakalema 2019), making it is suitable for our purpose of detecting charcoal kilns/kiln scars and surrounding bare soil. We observed that the spectral signatures of the three classes differed for Sentinel-2 data (Fig. 4c).

The RF algorithm requires the user to specify two parameters: (i) Ntree (i.e., number of trees) and (ii) Mtry (i.e., the number of input variables sampled to determine the splitting of each node) (Belgiu and Drăgu 2016). We tested the effect of a change from 0 to 8000 trees on the performance of the RF-algorithm (i.e., overall accuracy) for 10 sets of test and training data for both the Landsat-8 and Sentinel-2 data (see Appendix Fig. A5 and A6 for results). Because we observed a stabilization in performance at 1000 trees for both Landsat-8 and Sentinel-2 data, we set the Ntree parameter at 1000 trees (500 trees or more is recommended (Belgiu and Drăgu 2016)). The Mtry parameter introduces a penalization factor for the amount of input variables in the RF algorithm. It is calculated as the square root of the number of input variables (Belgiu and Drăgu 2016), which in our case is 22 for Landsat-8 and 14 for Sentinel-2.

### *2.4.2 Classification*

We used the field and visual inspection location data for the three classes of interest (charcoal, forest and non-forest sites) to train and test the two random forest classifiers. The dataset consisted of: (i) charcoal site location data collected in the field, and (ii) forest and non-forest site location identified through visual inspection of Worldview-2 data (see Section 2.2). We obtained 184 data points per class, and out of these we randomly selected 70% to train the classifier and used the other 30% to test its accuracy. Since the data used for training the classifier was not used to test accuracy, we can assume independence, fulfilling the assumptions of RF classification algorithms (Belgiu and Drăgu 2016). We selected the same number of data points per class because the random forest algorithm is sensitive to imbalanced training samples (Belgiu and Drăgu 2016). Because the randomization process to split training and test data can have an effect on the random forest outcome, we repeated it 30 times, each time randomly selecting 30% of the data for testing and 70% of the data for training from our sample of 184 points per class. We performed a RF on each of the 30 subsets and produced 30 RF classification maps of charcoal, forest and non-forest sites. We then produced a final ensemble map of charcoal sites across our study area for 2019, by selecting those pixels classified as charcoal sites 100% of the time over the 30 RF realizations. This procedure was adopted for both the Landsat-8 and the Sentinel-2 data; hence we produced two final ensemble maps, one for Landsat-8 and one for Sentinel-2.

### *2.4.3 Accuracy, uncertainty and importance assessments*

To assess model accuracy, we calculated classification accuracy metrics for each of the 30 RF realizations, based on test and training data. We calculated the average (i) internal (training data) and external (test data) overall accuracy, (ii) kappa coefficient, (iii) user and producer accuracies, and (iv) commission and omission errors (Banko 1998). All accuracy metrics are independent and assess model transferability (Janssen and van der Wel 1994), apart from the internal overall accuracy, which is dependent and is used to assess model fit (Adelabu *et al* 2015). We calculated our accuracy metrics over the 30 RF realizations because this provided us with information on the sensitivity of the results to the randomized selection of test and training data. We calculated the average classification accuracies per accuracy metric and its standard deviation over the 30 RF realizations to obtain a confidence interval around accuracy values. A sensitivity analysis of training samples is recommended, as sampling design and test and training data selection can affect accuracy estimates of classification outputs (Belgiu and Drăgu, 2016). To estimate accuracy over the final ensemble maps (maps including pixels classified as charcoal sites 100% of the time), we calculated the percentage of pixels that were classified as charcoal sites on the Landsat-8 and Sentinel-2 ensemble maps that overlapped with the charcoal site field data.

We complemented the accuracy metrics with a prediction uncertainty map calculated over our study area. We used Shannon's entropy as an indicator of RF prediction uncertainty (Calderón-Loor et al.,

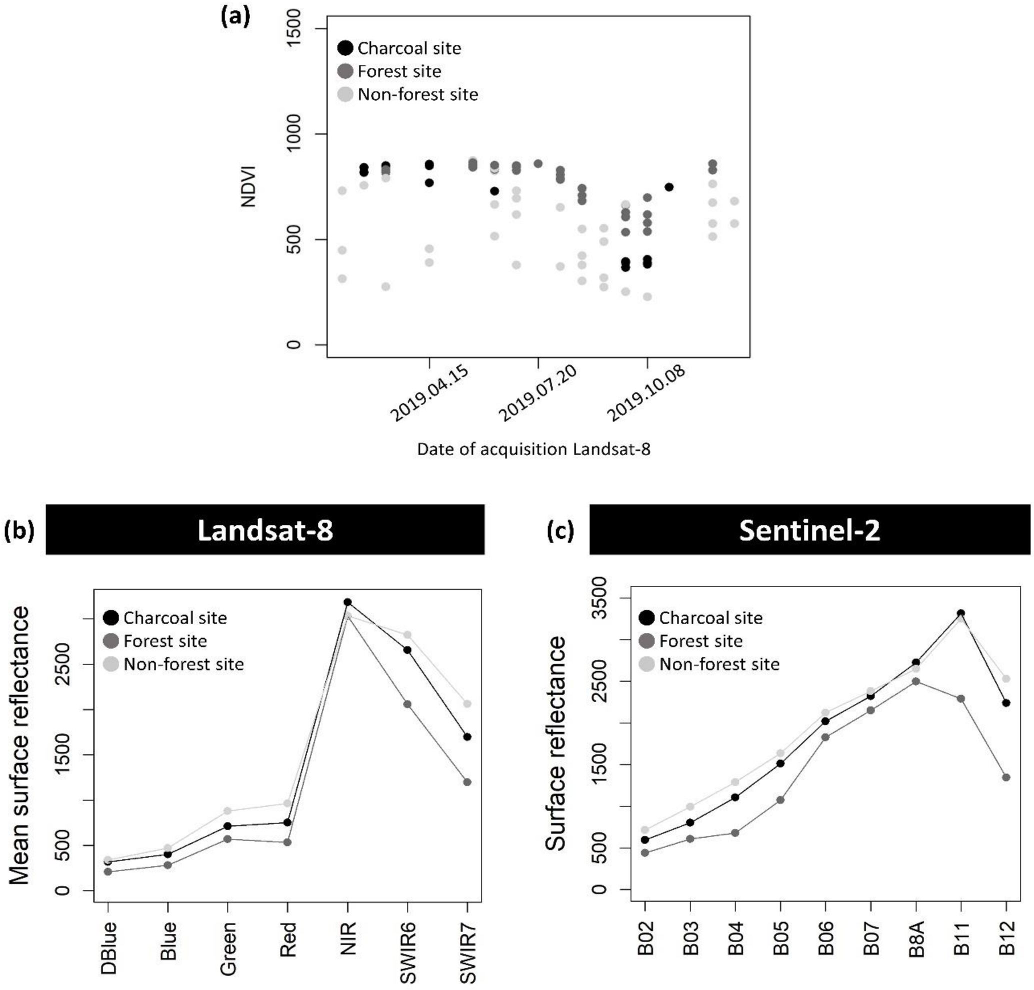

**Figure 4. (a)** Landsat-8 NDVI values of 3 randomly selected charcoal, forest and non-forest sites over time, calculated from the 19 images acquired in the year 2019. It can be observed that the dry season causes a drop in NDVI values for forest sites and that NDVI values of charcoal sites vary over the year, while non-forest sites show less variation throughout the year. **(b)** The average of the mean of surface reflectance for 7 Landsat-8 bands. **(c)** The mean of the surface reflectance for 9 Sentinel-2 bands. Landsat-8 and Sentinel-2 surface reflectance data was multiplied by 10,000 for purposes of display.

2021). Shannon's entropy estimates the average level of 'information' inherent to possible outcomes of the classifier (Shannon, 1948). In other words, it allows for an estimation of the robustness of membership attribution to a class of a given pixel. A low entropy value indicates low levels of uncertainty, i.e., the pixel is always classified as the same class over the 30 RF realizations, thus contains a high average level of information, while the opposite is true for high entropy. We used the 30 RF realizations to calculate a per-pixel Shannon entropy value for each Landsat-8 and Sentinel-2 classification map (Shannon, 1948), using the function "rasterEntropy" of the R-package "RStoolbox". The per-pixel Shannon entropy is calculated as:

$$E = -\sum p \, \log_2 p$$

, where $E$ = per-pixel entropy, and $p$ = per-pixel class frequency (charcoal, forest and non-forest sites). Minimum per-pixel entropy is 0, while maximum per-pixel entropy is 1.58 (based on the frequency distribution of 0.33 per class).

To interpret the RF models, we assessed variable importance by calculating: (i) Mean Decrease Gini and (ii) Mean Decrease Accuracy using the function "importance" of the R-package "randomForest" (Cutler et al., 2012). Mean Decrease Gini indicates the number of times a specific band or index is used to split a node in the RF, weighted by the number of split samples in the tree, measured with the Gini Index (Han *et al* 2016). Although Mean Decrease Gini provides a good overview of the importance of an input variable to the RF model, it is biased towards features with many unique values (Altmann et al., 2010). To account for this, we also calculated the Mean Decrease Accuracy by: (i) calculating the out-of-bag (OOB) error (i.e., mean prediction error) of each tree in the RF model, (ii) calculating the OOB error after permuting each of the predictor variables, (iii) calculating the difference between the two OOB errors averaged over all trees, and (iv) normalizing the difference between the two OOB errors by the standard deviation of the differences (Breiman et al., 2018). Mean Decrease Accuracy was calculated for each of the predictor variables and for the entire model. Together, the two measures of importance allowed us to determine the variables that contributed most to the Landsat-8 and Sentinel-2 RF models. Although the Mean Decrease Accuracy and Mean Decrease Gini results could have been used to pre-filter input data, we decided not to filter out bands or indices that were of limited importance to the classifier. This is justifiable because we have relatively few input variables for a RF classifier (Belgiu and Drăgu, 2016), and we wished to examine the importance of the different input variables to map multiple characteristics of charcoal sites. Additionally, previous studies suggest that no significant differences occur between RF classifiers for which outputs have been pre-filtered on redundant variables or variables of limited importance and those for which outputs have not been pre-filtered because the RF classifier utilizes embedded feature selection methods (Adelabu *et al* 2014, Dalponte *et al* 2013).

We conducted both the Landsat-8 and Sentinel-2 classifications in R for consistency (Team 2019). We pre-processed Sentinel-2 data in Python because it is easily downloaded using the "sentinelsat" library (https://github.com/sentinelsat), and easily processed using the "rasterio", "shapely" and "geopandas" libraries for spatial data processing in Python.

### *2.5 Method II: Visual inspection of charcoal kilns on VHR data*

We visually inspected Worldview-2 imagery from 2017, VHR imagery of 2019 in Google Earth, and Planet data from 2020 for charcoal kilns/kiln scars (Sedano et al., 2016). It is possible to visually observe charcoal kilns/kiln scars because they have specific shapes and colors (Sedano *et al* 2016). During and after the charcoal production process in the charcoal kiln, soil properties change, resulting in a difference in soil color and texture compared to surrounding soils (Gómez-Luna *et al* 2009, Oguntunde *et al* 2008). These differences in soil color and texture can be detected by the human eye (Sedano *et al* 2016). We used true color Worldview-2 and Planet images (Table 1), and visually inspected the images for the shapes of kilns/kiln scars (Fig. 5, Sedano et al. (2016)). Kiln scars change in shape and color with age (Fig. 5) and may be confused with other objects, such as tree outlines, nomad livestock farms, and burnt forest patches (Appendix Fig. A7), which affects their detectability to the human eye. The Planet data only covered parts of the study area and although certain images were relatively cloud-free, in several instances clouds prevented the visual detection of charcoal sites. As the Worldview-2 data of 2017 covered a wider area and less than 4% of the data was covered in clouds, a larger area could be inspected for charcoal sites. Therefore, the number of kilns/kiln scars detected on each VHR image does not provide an indication of the total number of charcoal sites that occur in our study site but rather indicates our ability to visually detect charcoal sites on VHR imagery of the years 2017, 2019 and 2020.

### *2.6 Method combination: charcoal classification robustness*

We combined output from the three methods ((i) RF Landsat-8, (ii) RF Sentinel-2 and (iii) visual inspection of Planet and Worldview-2) to benefit from the advantages of each method to target different characteristics of charcoal sites. We used this combined output to assess the robustness of the classified charcoal sites. We define robustness as the quantification of the likelihood of a site to be recognized as a charcoal site by both RF classification methods, with high classification robustness representing a charcoal site identified by two classification methods, and low classification robustness representing a charcoal site classified only by one of the two methods. By combining methods, we reduced the error associated with each individual method.

First, we calculated classification robustness for the Landsat-8 and Sentinel-2 RF classifiers. We calculated classification robustness as:

$$R_{class} = (C_{L8} + C_{S2}) - (E_{L8} + E_{S2})$$

, where $R_{class}$ is the classification robustness pixel value (30 m resolution), $C_{L8}$ is the probability of a pixel to be predicted as a charcoal site on the ensemble map produced by the Landsat-8 classifier (30 m resolution), $C_{S2}$ is the probability of a pixel to be predicted as charcoal site on the ensemble map produced by the Sentinel-2 classifier (20 m resolution). Those pixels classified as charcoal sites 100% of the time on the Landsat-8 or Sentinel-2 ensemble maps ($C_{L8}$ or $C_{S2}$) have a value 1. The $E_{L8}$ is the per-pixel entropy value computed over the 30 classification maps produced by the Landsat-8 classifier (30 m resolution), and $E_{S2}$ is the per-pixel entropy value computed over the 30 classification maps produced by the Sentinel-2 classifier (20 m resolution). The per-pixel entropy values range between 0 (minimum entropy) and 1.58 (maximum entropy). In other words, we accounted for spatial uncertainty by subtracting per-pixel entropy maps calculated over Landsat-8 and Sentinel-2 RF classification maps from the sum of the Landsat-8 and Sentinel-2 RF ensemble maps. With this calculation, we produced a continuous classification robustness measure of charcoal sites. Maximum classification robustness corresponds to a value of 2, where both the charcoal site ensemble maps of Landsat-8 and Sentinel-2 overlap and minimum entropy exists. Pixels not classified as charcoal sites 30 times on either the Landsat-8 or Sentinel-2 ensemble map were removed from the classification robustness map. We also removed the cloud covered areas of the Sentinel-2 image.

Second, we overlapped the classification robustness map with the location of the kilns/kiln scars, which we visually identified on VHR imagery. Through this procedure, we determined three levels of robustness of charcoal site detection: (i) high robustness: both maximum classification robustness and visually identified kilns/kiln scars, (ii) medium robustness: maximum classification robustness or

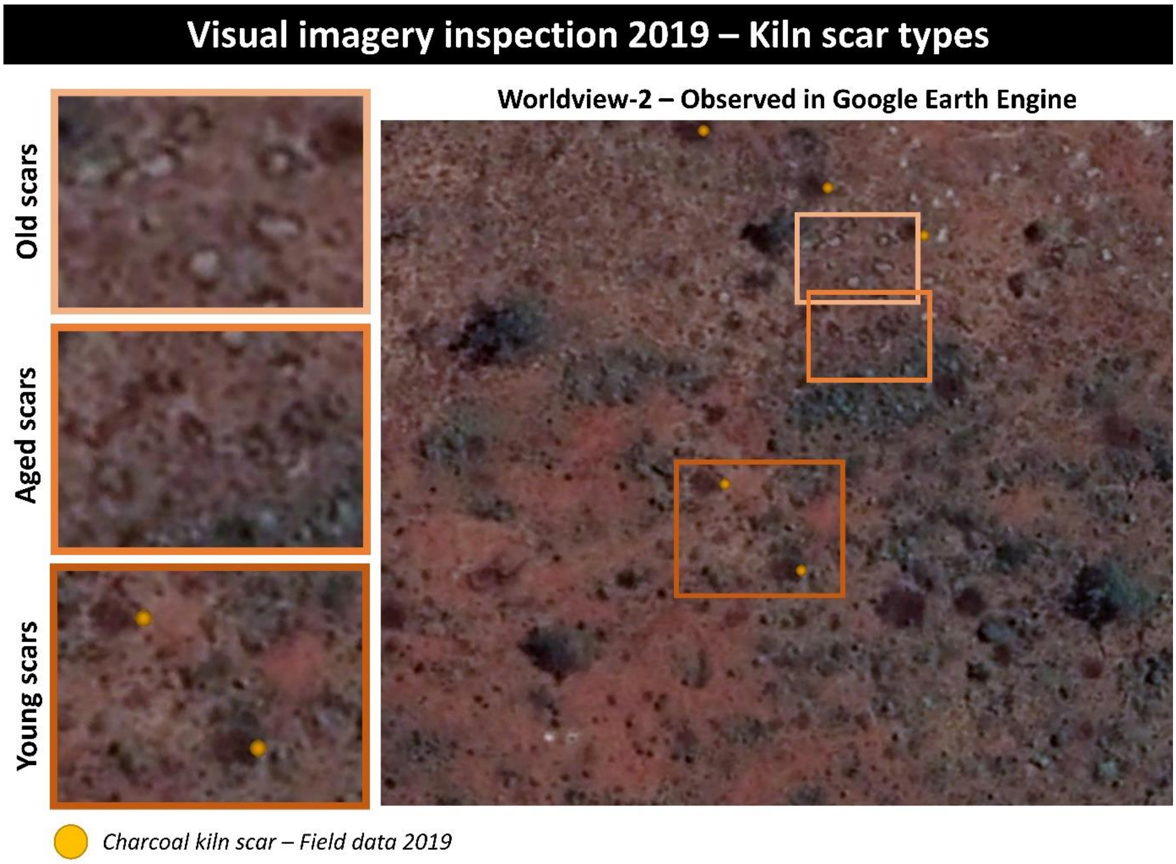

**Figure 5.** Charcoal kilns of different ages and sizes, visually detected in Google Earth for the year 2019 in a clear-cut area in one of the villages without a harvesting plan. The orange dots represent the charcoal kilns of which we acquired the location during our fieldwork campaign in August 2019. Young kiln scars are characterized by a dark color of fresh soil combined with dark charcoal fragments, while aged kiln scars are characterized by a circle of soil with a light inner spot of remaining charcoal fragments that have turned white. In old kiln scars, the remains of the kiln have become even whiter and are more spread over the area through weathering.

areas with identified kilns/kiln scars overlaying regions with lower than maximum classification robustness, and (iii) low robustness: lower than maximum classification robustness or areas where kilns/kiln scars were only identified through visual imagery inspection. This map allowed us to determine those regions that were more coherently classified as charcoal site across the three different methods and, therefore, provided the best possible (and most conservative) prediction of charcoal sites. In addition, the overlap of classified and visual imagery inspection output allows for an assessment of the extent to which classification methods may detect charcoal sites from the past (e.g., charcoal sites originating from 2017). Please note that this overlap does not provide an indication of the accuracy of visual imagery inspection, as there is a mismatch between the time of acquisition of the VHR and the Landsat-8 and Sentinel-2 imagery.

We used the classification robustness map overlapped with the kilns/kiln scars that we visually identified on VHR imagery to calculate areas with high, medium and low robustness by summing the number of 30 m pixels in each category. We then calculated the high, medium and low robustness area ($km^2$) and determined the percentage of the village area covered by charcoal sites of each category for both villages with a harvesting plan and without harvesting plan.

### *2.7. Effects of forest harvesting regimes on charcoal site detection*

We assessed effects of canopy cover on our ability to detect charcoal sites, and the robustness of this detection for all three methods. We considered three forest harvesting regimes with varying levels of canopy cover following charcoal production: (i) selective cutting, (ii) mixed cutting, and (iii) clear cutting (Fig. 6). We distinguished these harvesting regimes based on our experience in the field, the harvesting plan adopted in some villages, and the governance of charcoal production in Tanzania. We compared the number of pixels classified as charcoal sites with Landsat-8 and Sentinel-2 and vice versa in our study area. We also calculated the percentage of pixels with maximum classification robustness for charcoal sites on the Landsat-8 and/or Sentinel-2 ensemble maps over the entire study area and per village type, and compared these percentages between harvesting regimes.

## 3. Results

### *3.1 Characteristics of charcoal sites in the study region*

We found differences in charcoal sites between villages with and without a harvesting plan. In general, villages with a harvesting plan had smaller harvesting areas (635 $m^2$ to 5,870 $m^2$; average harvesting area = 2,318 ± 873 $m^2$) than villages without a harvesting plan (482 $m^2$ to 127,549 $m^2$; average harvesting area =11,581 ± 31,184 $m^2$). Additionally, villages with a harvesting plan had on average 1.7 ± 0.8 kilns/kiln scars per harvesting area (maximum = 3), while villages without a harvesting plan had 4.45 ± 5.4 charcoal kilns/kiln scars per harvesting area (maximum = 21). We also found both areas with large numbers of kilns/kiln scars concentrated together in villages without a harvesting plan and areas with scattered kilns/kiln scars; the former often in clear-cut areas and the latter mostly in selective cutting areas or scattered throughout the forest. Our field measurements showed that the average kiln (scar) size was relatively larger (length = 8.2 ± 3.0 m, width = 3.7 ± 1.6 m) in villages with than in villages without a harvesting plan (length = 5.6 ± 2.3 m, width = 2.5 ± 0.8 m).

### *3.2 Method I: Charcoal site classification with Landsat-8 and Sentinel-2*

Landsat 8: We classified charcoal, forest and non-forest sites for 2019 with an average overall accuracy of 82.27 ± 2.40%, and a kappa coefficient of 74.09 ± 3.60% for the test data. The small standard deviations show limited sensitivity of the RF classifier to test and training data selection. Internal accuracies were 100%. User and producer accuracies for charcoal sites were 78.91 ± 5.28% and 75.29 ± 4.76%, respectively, and were lower than those of forest and non-forest sites (Table 2). We determined that 62% of 184 charcoal field locations overlapped with pixels classified as charcoal site 100% of the time on the Landsat-8 ensemble map, whereas only 38% charcoal site field locations overlapped with pixels classified as forest and/or non-forest site at least once throughout the 30 RF realizations.

**Table 2.** Error matrix for the average classification of test points (n = 165) over 30 random forest outputs for the Landsat-8 classification for 2019. PA: Producer Accuracy; UA: User Accuracy; CE: Commission Errors; OE: Omission errors.

| | Charcoal | Non-forest | Forest | Total | UA (%) | CE (%) |
|---|---|---|---|---|---|---|
| **Charcoal** | 43.40 | 5.80 | 8.70 | 57.90 | 78.91 | 21.09 |
| **Non-forest** | 5.60 | 48.93 | 2.13 | 56.67 | 88.86 | 11.14 |
| **Forest** | 6.00 | 0.27 | 44.17 | 50.43 | 80.40 | 19.60 |
| **Total** | 55.00 | 55.00 | 55.00 | 165 | | |
| **PA (%)** | 75.29 | 86.55 | 87.71 | | | |
| **OE (%)** | 24.71 | 13.45 | 12.29 | | | |

The most important input variables to the 30 RF models based on Landsat-8 data were the mean of Band 3 (Green), followed by the mean of Bands 4 (Red), 2 (Blue), and 7 (SWIR) (Appendix Table A2). More specifically, the most important variables for charcoal site classification were the mean of Bands 3, 1 (Coastal aerosol), 6 (SWIR), and 4, while the most important variables for forest and non-forest sites classification were the mean of Bands 3 and 7 (Appendix Table A2). The mean of bands and indices generally provided more important information to the classifier than the coefficient of variation of bands and indices.

Sentinel-2: We obtained an average external overall accuracy of 83.56 ± 2.82% and a kappa coefficient of 75.32 ± 4.23% for the test data. Low standard deviations suggest little sensitivity of the classifier to random test and training data selection. Internal accuracies were 100%. Producer and user accuracies for charcoal sites were 82.47 ± 4.61% and 78.34 ± 2.17%, respectively (Table 3). Accuracies for charcoal sites were lower than those for forest and non-forest sites. We calculated that 65% of 184 charcoal field locations overlapped pixels classified 100% of the time as charcoal site in the Sentinel-2 ensemble map, whereas 34% overlapped with pixels classified as forest and/or non-forest site at least once throughout the 30 RF realizations.

**Table 3.** Error matrix for the average classification of test points (n = 159) over 30 random forest outputs for the Sentinel-2 classification for 2019. PA: Producer Accuracy; UA: User Accuracy; CE: Commission Errors; OE: Omission errors. The lower total numbers compared to Landsat-8 are due to the occurrence of cloud cover on the processed Sentinel-2 image.

| | Charcoal | Non-forest | Forest | Total | UA (%) | CE (%) |
|---|---|---|---|---|---|---|
| **Charcoal** | 45.45 | 4.07 | 8.55 | 58.07 | 78.34 | 21.66 |
| **Non-forest** | 3.90 | 45.31 | 2.03 | 51.24 | 88.20 | 11.80 |
| **Forest** | 5.66 | 1.62 | 42.41 | 49.69 | 85.54 | 14.46 |
| **Total** | 55.00 | 51.00 | 53.00 | 159 | | |
| **PA (%)** | 82.47 | 88.80 | 79.70 | | | |
| **OE (%)** | 17.54 | 11.20 | 20.30 | | | |

On average the most important variable to the Sentinel-2 RF classifier was Band 3 (Green), with additional important contributions of NBR, Band 2 (Blue), and 11 (SWIR) (Appendix Table A3). More specifically, the most important variables for charcoal site prediction were Bands 3, 11, 2, and BSI in order of importance, while the most important variables to predict forest sites were NDWI, NBR, and Bands 11 and 12 (SWIR), and the most important variables to predict non-forest sites were Bands 3, 2, BNR and NDWI (Appendix Table A3).

### *3.3 Method II: Visual inspection of charcoal kilns on VHR data*

Overall, 2,734 kilns/kiln scars were visually detected in villages without a harvesting plan in contrast to 281 kilns/kiln scars in villages with a harvesting plan, totaling 3,015 kilns/kiln scars. We identified 1,547 kilns/kiln scars on the 2017 Worldview-2 data, 298 kilns/kiln scars on the 2019 VHR data (only one village without a harvesting plan) and 1,170 kilns/kiln scars on the 2020 Planet data. Of the kilns we visited during our field campaign, we could only visually identify those located in clear cutting areas, because canopy cover prevented us from observing those in selectively cut areas.

### *3.4 Charcoal robustness analysis*

Figure 7 visualizes three different levels of robustness of charcoal site detection that can be identified on the classification robustness map (see Section 2.6) overlaid by visually inspected kilns and kiln scars on VHR satellite data (see Section 2.5). The figure shows: (i) low robustness areas with lower than maximum classification robustness or identified kilns/kiln scars that do not overlap with either the Landsat-8 or Sentinel-2 ensemble maps, (ii) medium robustness areas with maximum classification robustness or lower than maximum classification robustness in the presence of visually identified kilns/kiln scars, and (iii) high robustness areas with maximum classification robustness in the presence of visually identified kilns/kiln scars.

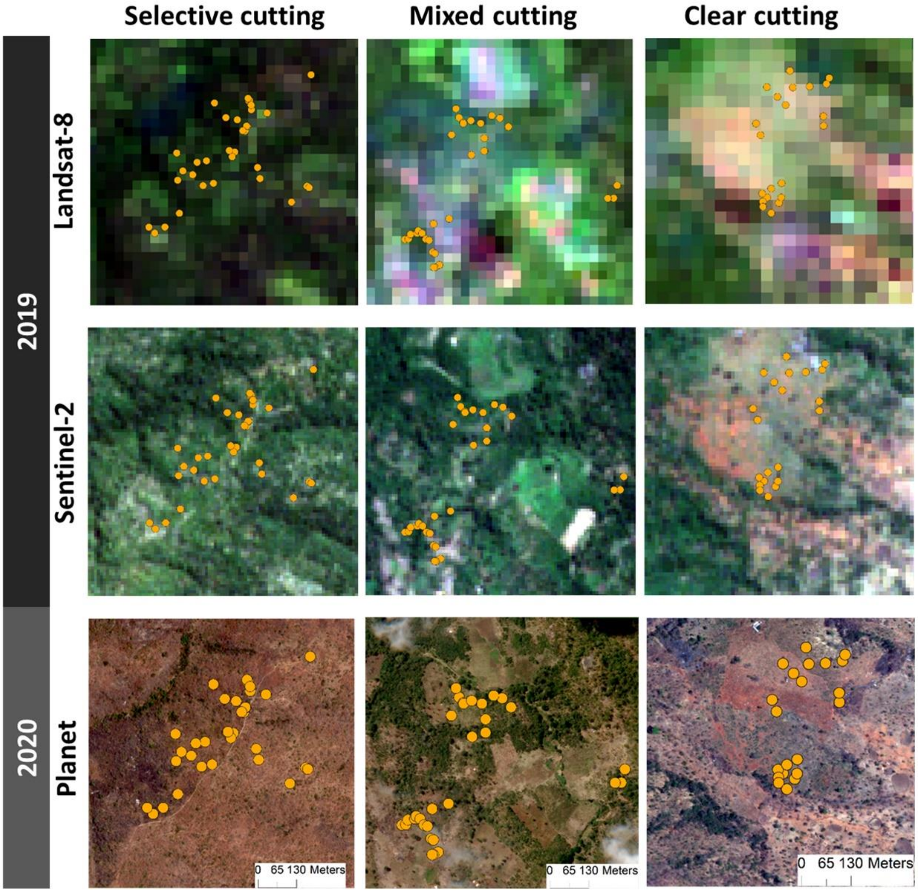

**Figure 6.** Study region areas with different harvesting regimes for charcoal production. The yellow dots represent the locations of charcoal kilns obtained during the field campaign of August 2019. We defined selective cutting areas as those where charcoal production occurs as dictated a harvesting plan introduced under the TTCS project of TFCG, mixed cutting as areas with a combination of clear cutting and selective cutting, and clear cutting as areas that have become bare following harvesting of biomass for charcoal production. We only included Planet imagery in this figure, and not Worldview-2, because these imagery have approximately the same resolution and provide the same image overview.

*High robustness sites*: 237 visually inspected kilns/kiln scars overlapped with 30 m maximum classification robustness pixels and were, therefore, labelled high robustness sites. We calculated a combined high robustness area of 0.21 km$^2$, covering 0.06% of the study area after cloud removal (Fig. 7). Of the 247 high robustness charcoal sites, 232 (97.89%) were found in villages without a harvesting plan.

*Medium robustness sites*: 21,516 pixels exhibited maximum classification robustness; a combined medium robustness area of 19.36 km$^2$, covering 5.67% of the study area after cloud removal. Of these pixels, 17,197 were in villages with a harvesting plan, covering an area of 15.48 km$^2$, which corresponded to 6.42% of the village areas. The remaining 4,319 pixels were found in villages without a harvesting plan, covering an area of 3.89 km$^2$, which corresponded to 3.88% of the village areas.

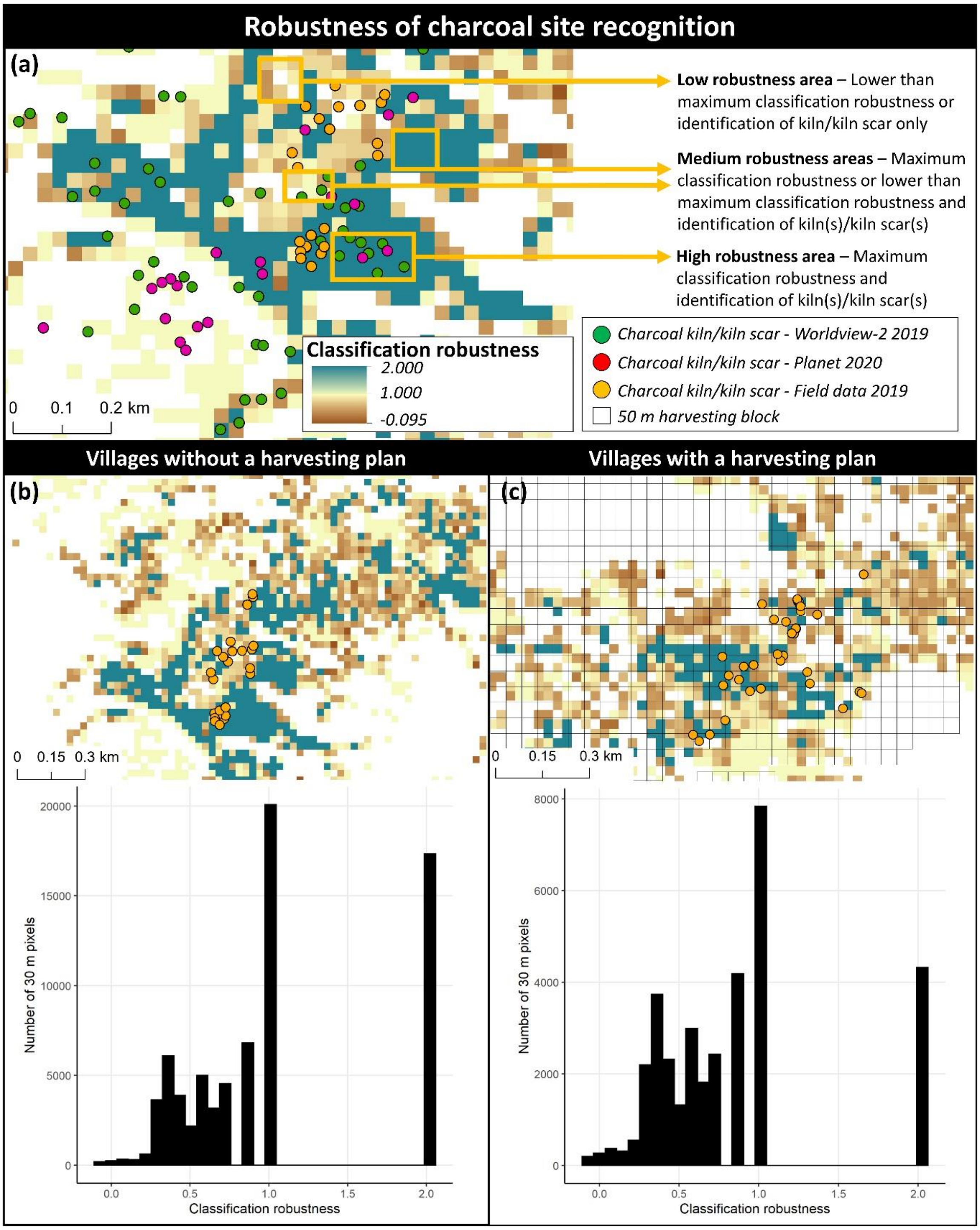

**Figure 7. (a)** Charcoal sites detected with different levels of robustness in a clear cutting area in one of the villages without a harvesting plan. **(b)** *Upper*: Classification robustness in an area with mixed and clear cutting of a village without a harvesting plan. *Lower*: Frequency distribution of classification robustness for the areas classified as charcoal site on the Landsat-8 and/or Sentinel-2 ensemble maps in villages without a harvesting plan. **(c)** *Upper*: Classification robustness in an area with selective cutting of a village with a harvesting plan. The 50 m squares show the harvesting blocks available to charcoal producers following a checkerboard pattern (Ishengoma et al. 2016). *Lower*: Frequency distribution of classification robustness for the areas classified as charcoal site on the Landsat-8 and/or Sentinel-2 ensemble maps in villages with a harvesting plan

Besides this, 765 visually inspected kilns/kiln scars covered 30 m charcoal site pixels with less than maximum classification robustness; a combined medium robustness area of 0.68 km$^2$, covering 0.20% of the study area. Of these visually inspected kilns/kiln scars 615 (80.39%) were in villages without a harvesting plan, covering a combined area of 0.55 km², i.e., 0.23% of the villages. In total, medium robustness sites spanned an area of 20.05 km², i.e., 5.87% of the study area.

*Low robustness sites*: 86,917 pixels had lower than maximum classification robustness; corresponding to a combined low robustness area of 78.23 km², covering 22.90% of the study area after cloud removal. Of these pixels, 56,381 were located in villages with a harvesting plan, covering an area of 50.74 km² (50.59% of the villages). The remaining 30,536 pixels were found in villages without a harvesting plan, covering an area of 27.48 km² (11.39% of the village areas). Besides this, 2,013 visually inspected kilns/kiln scars did not cover any pixels identified as charcoal site on the Landsat-8

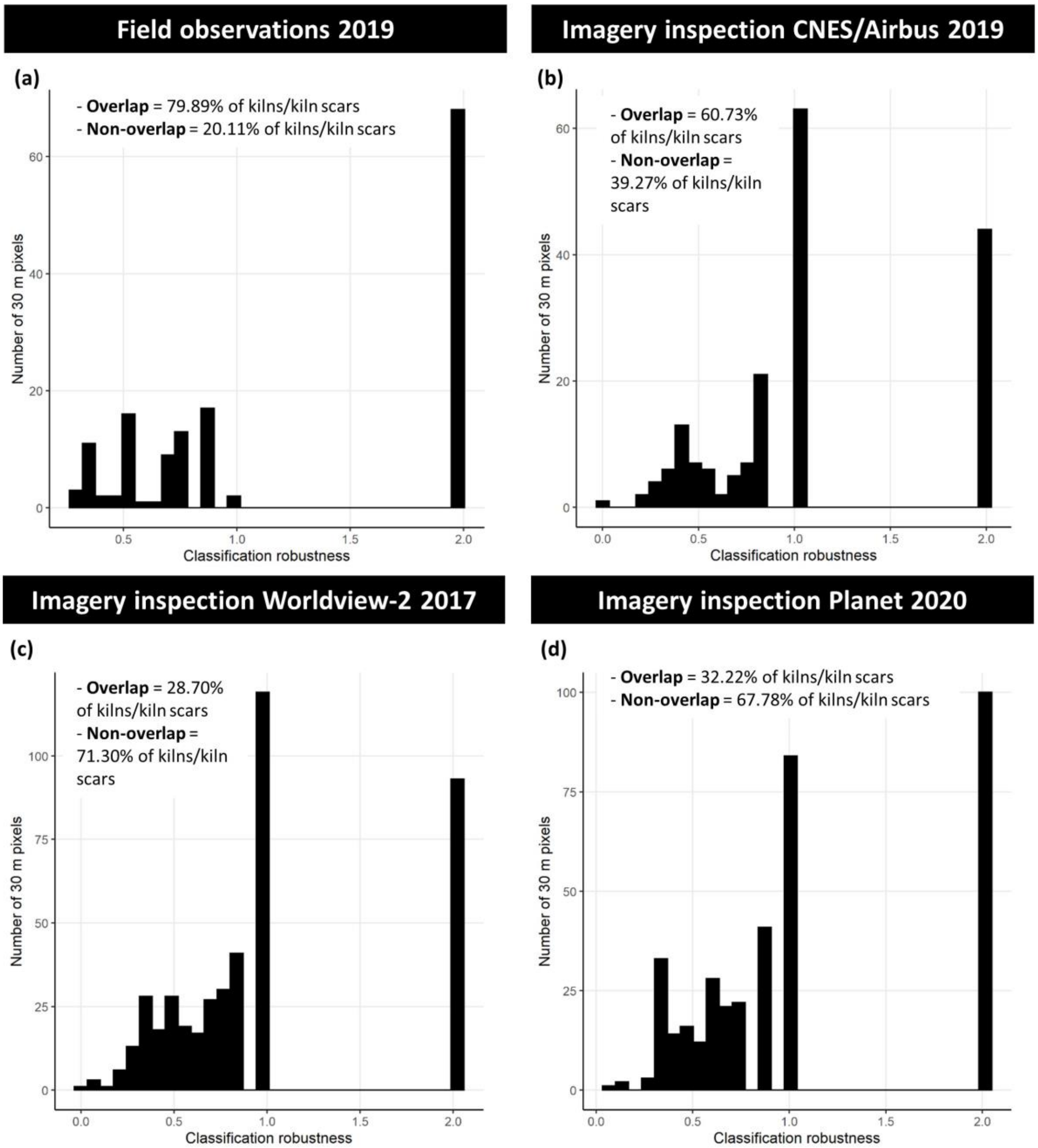

**Figure 8. (a)** Frequency distributions of classification robustness for the kilns/kiln scars located during our fieldwork study in August 2019. **(b)** Frequency distributions of classification robustness for the kilns/kiln scars located through imagery inspection of VHR data of CNES of 2019 observed in Google Earth for one of the villages without a harvesting plan. **(c)** Frequency distributions of classification robustness for the kilns/kiln scars located through imagery inspection of Worldview-2 data of 2017 © Maxar Technologies (2017), provided by European Space Imaging through the ESA third party program. **(d)** Frequency distributions of classification robustness for the kilns/kiln scars located through imagery inspection of Planet data of 2020.

or Sentinel-2 ensemble maps; a combined low robustness area of 1.81 km$^2$ (measured in 30 m pixels) covering 0.53% of the study area. Of these visually inspected kilns/kiln scars, 1,170 (58.12%) were found in villages without a harvesting plan, covering a combined area of 1.05 km$^2$, corresponding to 0.44% of the villages. In total, 843 kilns/kiln scars (41.88%) were found in villages with a harvesting plan, covering a combined area of 0.76 km$^2$, corresponding to 0.69% of the village area. In total, low robustness sites spanned an area of 80.04 km$^2$, equaling 23.43% of the study area.

Most of the kilns/kiln scars observed in the field (147 out of 184 (79.89%)) overlapped pixels classified as charcoal sites on the Landsat-8 and/or Sentinel-2 ensemble maps, and the majority was located in areas with maximum classification robustness; shown in Figure 8a as the frequency distributions of classification robustness of kilns/kiln scars. We also observed that the majority of the visually inspected kilns/kiln scars on VHR data of 2019 (60.73%) overlapped with areas identified as charcoal site on the Landsat-8 and/or Sentinel-2 ensemble maps. However most of these overlapping areas have a lower than maximum classification robustness (Fig. 8b). For visually inspected Worldview-2 and Planet data of 2017 and 2020, we find that most of the observed kilns/kiln scars do not overlap with charcoal sites detected on the Landsat-8 and/or Sentinel-2 ensemble maps (only 28.70% and 32.22% overlaps, respectively) (Fig. 8c,d). Nevertheless, a relatively large proportion (100 out of 277 observed kilns/kiln scars (36.10%)) of observed kilns/kiln scars on Planet imagery of 2020 are positioned on pixels with maximum classification robustness (Fig. 8d).

### *3.5. Effects of canopy cover on charcoal site detection*

We observe a higher proportion of predicted charcoal sites with maximum classification robustness in villages without a harvesting plan (23.41% of all pixels classified as charcoal site on the ensemble maps) than in villages with a harvesting plan (12.41% of all pixels classified as charcoal site on the ensemble maps) (Fig. 7). The area predicted as charcoal site on the Landsat-8 ensemble map covers 14.89% of the villages without a harvesting plan after cloud removal, compared to 20.24% of the villages with a harvesting plan. In contrast, the area predicted as charcoal site on the Sentinel-2 ensemble map covers 29.64% of the villages without a harvesting plan compared to 9.48% of the villages with a harvesting plan. The remaining area was classified as either forest or non-forest site on the Landsat-8 and Sentinel-2 ensemble maps.

We observe that charcoal sites with high classification robustness spanned relatively large continuous areas in villages without a harvesting plan, while those in villages with a harvesting plan were scattered and only formed small patches (Fig. 7). We observe that this pattern corresponds to the different harvesting regimes, where charcoal producers in villages with a harvesting plan produce smaller charcoal sites due to restrictions on harvesting area size and shape, while charcoal producers in villages without a harvesting plan produce charcoal sites of a range of different sizes and shapes because they do not adhere to a harvesting plan or rules and regulations for production. This is even more evident when zooming into patches of selective, mixed and clear cutting for charcoal production (Fig. 9). More pixels were classified as charcoal sites on the Sentinel-2 ensemble map than on the of Landsat-8 ensemble map in clear cutting areas and, to a certain extent, mixed cutting areas. Sentinel-2 classification maps also overlapped more with the charcoal sites observed in the field, in particular in clear cutting areas.

## 4. Discussion

In this study, we achieve charcoal site detection with high robustness through a novel method that combines two RF classification algorithms based on Landsat-8 and Sentinel-2 data with visual inspection of VHR imagery. Our results allow for the identification of areas with the highest likelihood of charcoal production. We hypothesized that each individual method benefits from particular characteristics of charcoal sites, namely (i) the phenology of the harvesting areas for charcoal production (Landsat-8), (ii) the kiln/kiln scar and surrounding bare soil (Sentinel-2), and (iii) the kiln/kiln scar itself (VHR Worldview-2 and Planet data). The ability of the combined remote sensing approach to detect charcoal sites varied with harvesting intensity, with higher robustness in clear cutting areas and lower robustness in selectively cut areas. We find that combining Landsat-8 and Sentinel-2 classification methods and accounting for classification uncertainty, allows for a more robust detection of charcoal sites in selective cutting areas, where canopy cover prevents the visual inspection of kilns/kiln scars. Our results encourage the use of a combined remote sensing method to study and monitor charcoal production and its impact on forests and ecosystem services.

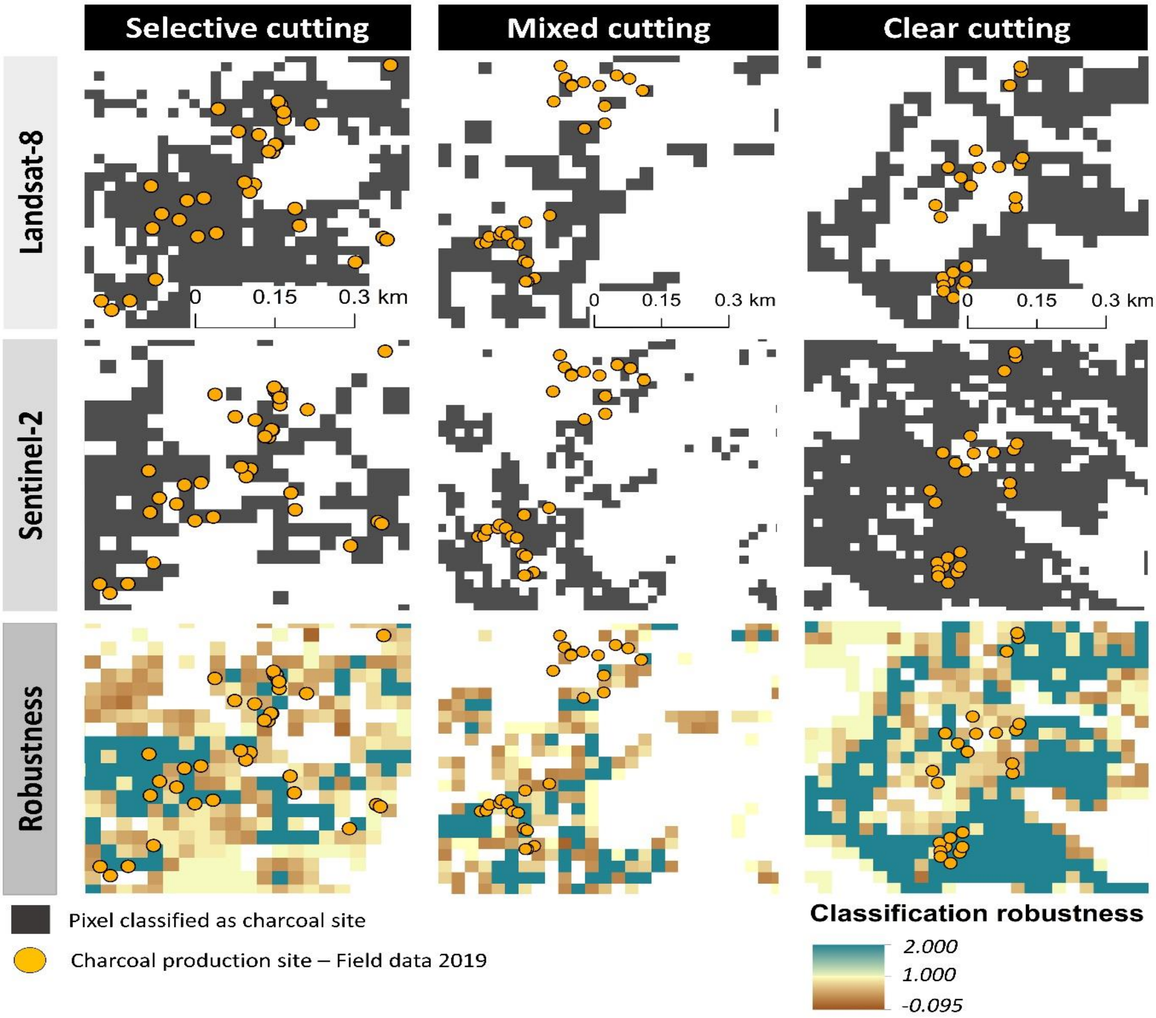

**Figure 9.** Charcoal site classification and classification robustness for Landsat-8 and Sentinel-2 ensemble maps shown for the selective, mixed and clear-cutting areas of Figure 3. The Sentinel-2 classifier classifies more pixels as charcoal sites in clear cutting areas than the Landsat-8 classifier. Scattered pixels classified as charcoal sites are observed in mixed or selectively cut areas. The orange dots represent the GPS locations of charcoal sites observed in the field.

### *4.1 Landsat-8 and Sentinel-2 classification*

Despite the variability in charcoal site characteristics, our RF classification method produces high accuracies and robustness for Landsat-8 and Sentinel-2, and we find low sensitivity to test and training data (standard deviations between 2.40% and 2.82% for Landsat-8 and Sentinel-2 RF classifications, respectively). The relatively lower user accuracies for charcoal sites compared to forest and non-forest sites for both Landsat-8 and Sentinel-2 (Tables 2 and 3), indicate that charcoal sites are more often confused with forest and non-forest sites than forest and non-forest sites are confused with each other. This likely results from the variable nature of charcoal sites, and the variation in canopy cover related to different harvesting regimes (Fig. 6), as well as the different tree species present, each with their own crown size and texture (Campbell 1996b). For Landsat-8 classification, charcoal sites are most often confused with forest sites (Table 2). This suggests misclassification between natural forest and charcoal sites, which occurs most often in villages with a harvesting plan, indicating that selectively cut charcoal sites are confused with natural forests. This suggests that only a small fraction of biomass is harvested in these selectively cut charcoal sites, causing aboveground biomass levels to remain within the natural range of variability of that of undisturbed forest sites. This also explains the larger charcoal site area predicted on the Landsat-8 ensemble map (20.24%) than the Sentinel-2 ensemble map (9.48%) in villages with a harvesting plan, and corroborates our expectation that the Landsat-8 classification method better differentiates harvesting areas of charcoal sites from forest sites. These results also justify the relatively low overlap between Sentinel-2 and Landsat-8 ensemble maps and the lower classification robustness observed in selectively cut forest (Fig. 9). The small harvesting areas of charcoal sites in villages with a harvesting plan (635 $m^2$ to 5,870 $m^2$, i.e. 7 to 65 of the 30m pixels), may challenge their detection on 30 m resolution Landsat-8 data. This is evident from the small differences in surface reflectance between charcoal, forest and non-forest sites for Landsat-8 (Fig. 4b, Appendix Fig. A9). This may explain the relatively higher overall accuracies for Sentinel-2 (83.56 ± 2.82%) than for Landsat-8 (82.27 ± 2.40%), as Sentinel-2 data shows larger differences in surface reflectance between charcoal, forest and non-forest sites (Fig 4c, Appendix Fig. A8). For the Sentinel-2 classification, charcoal sites are most often confused with non-forest sites, which corroborates our hypothesis that the Sentinel-2 RF classifier mainly receives signals from kiln/kiln scars, which can easily be confused with bare soil in clear cutting areas (Table 2. This suggests that the origins of misclassification mainly lie between charcoal sites and forest sites for Landsat-8 and between charcoal sites and bare soil for Sentinel-2.

Our results show that both Landsat-8 and Sentinel-2 classifications have an internal accuracy of 100%. This could result from over-prediction of charcoal sites, as found in prior studies using Sentinel-2 based methods (Nakalema, 2019). The classification results in the Sentinel-2 may suggest over-classification, which could have resulted from a mixture of signals from current and past charcoal sites, as suggested by the results in Appendix Fig. A10. Additionally, Sentinel-2 may not only distinguish signals from kilns/kiln scars and their surrounding bare soil, especially in clear cutting areas harvesting regimes, but also from harvesting areas for charcoal production (see Section 4.1.2). This likely causes over-prediction by the RF Sentinel-2 classifier in villages without a harvesting plan because these villages are mainly subjected to clear and mixed cutting, producing scattered charcoal sites with large ranges in the extent of canopy cover. In contrast, the Landsat-8 RF classifier mainly recognizes recent greening-up of regenerating harvesting areas because of the relatively lower spatial resolution of Landsat-8 compared to Sentinel-2 imagery and the time series we used (see Section 4.1.1). This challenges the differentiation of harvesting areas of charcoal sites from natural forest sites in selectively cut areas, where the spectral signals of harvesting areas and natural forest sites overlap, which explains over-prediction of the Landsat-8 RF classifier in villages with a harvesting plan. Additionally, the Landsat-8 RF classifier may fail to distinguish clear cutting areas with high accuracy, which may explain the disparity between the visually inspected kilns/kiln scars on VHR imagery and charcoal sites classified by the Landsat-8 RF classifier in villages without a harvesting plan. Besides this, over-prediction may generally result from our relatively small test and training data sample size in relation to the extent of our study area (Colditz 2015). Colditz (2015) indicates that RF classifiers perform best with sampling intensities of 0.25% of the study area, which in our case is about 0.05%. However, it is worth mentioning that the ideal coverage of training sample data is almost never reached for regional studies, yet classification may still provide adequate results as shown in a study that used 20,000 training points of 30 m to inform the classification of Australia (7.692 million $km^2$) (Calderón-Loor *et al* 2021).

#### *4.1.1 Importance of bands and indices for the Landsat-8 classifier*

The importance of Band 3 (Green) for the Landsat-8 classifier can be related to the relatively higher mean surface reflectance in charcoal sites than in forest sites (Appendix Fig. A9), and is in line with our expectation that Landsat-8 time series detect the phenology and greenness of the vegetation in harvesting areas (Table 1) (Aguilar 2005). Previous studies found that Landsat TM Green Band reflectance is correlated with forest age (e.g., coniferous and tropical) (Grabska and Socha 2021, Jakubauskas 1996, Boyd *et al* 1996), with high values indicating a regenerative forest stage and lower values a more mature forest stage (Boyd *et al* 1996, Grabska and Socha 2021). This because tree composition changes to more shade tolerant species with higher chlorophyll content of leaves as forests age (Gratani and Foti 1998, Sack *et al* 2003), which reduces reflectance in the green spectrum (Aguilar 2005), as has also been observed in miombo woodlands (Ribeiro *et al* 2021). This is due to an inverse relationship of the Green band surface reflectance to leaf chlorophyll concentration (Gitelson *et al* 1996, Virtanen *et al* 2020), which explains the relatively lower surface reflectance of the Green

Band for forest than for charcoal sites, as (many of) the charcoal sites assessed in our study are in early regenerative state (Appendix Fig. A9), likely dominated by early succession species with a different chlorophyll content than late succession species. Additionally, differences observed between forest and charcoal sites could have been amplified by intensive grazing by cattle, which changes plant species composition, induces tree coppicing and enhances seedling regeneration (Mtimbanjayo and Sangeda, 2018). As our study area includes areas used for livestock by nomadic pastoralists (Appendix Fig. A7), it is likely that regenerating charcoal sites are affected by grazing, which may have contributed to differences in surface reflectance in the Green band.

Other important bands for the Landsat-8 classifier were Band 7 (SWIR) and Band 4 (Red), where Band 7 discriminates the soil moisture content (Liu *et al* 2021, Rock *et al* 1986), and Band 4 detects chlorophyll content and shadowing of vegetation (Aguilar 2005). Older forest stands provide more shadow and more moist canopy conditions than regenerating forests (Vieira *et al* 2003). Correlations between SWIR and the regeneration stage of tropical forests have been observed in previous studies (Diniz *et al* 2021, Vieira *et al* 2003). Potential changes in soil moisture content in charcoal sites may relate to the carbonization process, which produces heat and, therefore, may reduce soil moisture in the area around the kiln (Badía et al., 2017). However, this process likely has limited influence considering that the 30 m spatial resolution of Landsat-8 exceeds the kiln and kiln scar area. Similarly to Band 3, the mean surface reflectance values of Band 4 are higher for charcoal sites, which indicates that vegetation in charcoal sites absorbs less light of this range than older forest stands (Appendix Fig. A9) (Horler *et al* 1983, Grabska and Socha 2021). Denser and darker canopy cover likely occurs in older forest stands (Gratani and Foti 1998, Sack *et al* 2003), explaining the relatively higher absorption of surface reflectance of the Red band in forest sites compared to charcoal sites. Nonetheless, we find more similarities in the mean surface reflectance of Band 7 and 4 between charcoal and forest sites than between charcoal and non-forest sites (Appendix Fig. A9), which indicates that the Landsat-8 RF classifier may more accurately distinguish charcoal sites from non-forest than from forest sites. This explains the higher misclassification of charcoal site test data as forest than as non-forest sites (Table 2).

Mean NDVI was of limited importance for the Landsat-8 RF classifier (Appendix Table A2), despite its sensitivity to chlorophyll concentrations in the canopy of young and growing vegetation (Vanderhoof *et al* 2021). Although charcoal sites show a relatively lower mean NDVI than forest areas, we observe a large overlap between mean NDVI ranges for the two classes (Fig. 4a), as well as for non-forest sites, explaining the lack of importance of NDVI to the classifier. Overlap of NDVI values between regenerative stages and older forests has been observed in previous studies, which show that NDVI unreliably discriminates between regenerative forest stages (Huang *et al* 2021, Irteza *et al* 2021). Additionally, NDVI is more sensitive to changes in herbaceous vegetation and short-term variation in precipitation than to changes in woody vegetation and long-term variations in precipitation, which has also been observed in miombo woodlands (Andela *et al* 2013). We used the mean and coefficient of variation of NDVI over the year 2019, which indicates long term rather than short term variations in precipitation. Charcoal sites are often not completely deforested due to selective cutting, and stems of trees often remain in place and quickly coppice after harvesting (Kouami *et al* 2009), which may explain the overlap in mean NDVI of charcoal sites with the mean NDVI of forest and non-forest sites. Previous research found that tree coppicing following harvesting for charcoal production is about 50% regardless of stump diameter, with an average of 6 coppices per stump (Sangeda and Maleko 2018). Hence, fast and robust regeneration of miombo woodlands following charcoal production (Sangeda and Maleko 2018) could affect NDVI. Miombo woodlands are known to experience peaks in NDVI four to six weeks before the start of seasonal rains due to blossoming and appearance of new shoots in *Brachystegia* species, the most dominant species of miombo woodlands (Davenport 1987). Further, miombo woodlands shed their leaves in the dry season to retain moisture (Frost 1996, Vinya *et al* 2018), likely affecting the amount of chlorophyll that can be detected during these periods (Davenport 1987). Together, the phenological variability in chlorophyll concentrations likely affects the mean NDVI signal and explains its overlap between charcoal and forest sites (Fig. 4a). Limited importance of NDWI, BSI and NBR indicates that Landsat-8 detects the harvesting area of charcoal sites, rather than the kiln/kiln scar and surrounding bare soil, corroborating our original expectation.

The relatively larger importance of the mean rather than the coefficient of variation of Landsat-8 bands and indices (Appendix Table A2), suggests that temporal variation in charcoal production sites were less intense than expected based on NDVI changes observed in previous studies (Sedano *et al* 2020a, 2020b). This may potentially be explained by the two distinct rainy seasons in miombo woodlands, which cause sharp variations in charcoal, forest and non-forest sites alike (Fig. 4a). This also suggests that charcoal sites in miombo woodlands differ from other types of forest degradation, challenging their detection based on temporal variations in vegetation indices. Further research on understanding these differences is warranted.

#### *4.1.2 Importance of bands and indices for the Sentinel-2 classifier*

Like for the Landsat-8 classifier, Band 3 (Green) is most important for the Sentinel-2 RF classifier, suggesting that it distinguishes signals of vegetation status and regeneration in charcoal sites (see Section 4.1.1). However, whereas Band 3 is important in the differentiation of charcoal, forests and non-forest sites alike in the Landsat-8 classifier (Appendix Table A2), it is mainly important for the differentiation of charcoal sites from non-forest sites in the Sentinel-2 RF classifier (Appendix Table A3). This indicates that Band 3 allows the Sentinel-2 RF classifier to differentiate between charcoal and non-forest sites, rather than between charcoal and forest sites, as shown by the relatively larger overlap in Band 3 reflectance between charcoal and forest sites than between charcoal and non-forest sites (Appendix Fig. A8). Instead, NDWI appears to be most important in distinguishing forest sites from charcoal and non-forest sites in the Sentinel-2 RF classifier (Appendix Table A3), as shown by a higher NDWI in forest sites than charcoal and non-forest sites (Appendix Fig. A4). This suggests that the Sentinel-2 RF classifier likely detects two important processes in charcoal sites: (i) (woody) vegetation growth in charcoal sites that distinguishes them from largely bare non-forest sites, and (ii) low water status in vegetation and soil surrounding the kiln/kiln scar related to heat combustion from charcoal production, which distinguishes charcoal sites from forest sites, where vegetation water content has not been affected by heat. The importance of NDWI for charcoal classification by the Sentinel-2 RF classifier (Appendix Fig. A3) is in line with our expectation that the classifier distinguishes kilns/kiln scars and surrounding (bare/burnt) areas (Table 1), where the lower NDWI in charcoal sites than in forest sites likely reflects the charcoal kiln (and its scar) and effects of heat stress on vegetation and soil around the kiln (Boyer and Lopez-Corona 2009, Gao 1996). Active kilns can reach temperatures between 300 and 500 °C, and the amount of heat released is similar to that of bushfires and slash-and-burn activities (Oguntunde *et al* 2008). Research indicates that drought stress can persist for months (Saatchi *et al* 2013), hence drought stress from charcoal production may remain evident for a relatively long period following the charcoal combustion process. This intensity of heat stress may not only affect vegetation but may also reduce soil moisture content (Badía *et al* 2017, Bannari *et al* 2020), which could further explain the importance of NDWI, as this index is sensitive to soil moisture fluctuations (Gu *et al* 2008, Jackson *et al* 2004). While NDWI removes the impact of vegetation on soil moisture (Gu *et al* 2008), it is more influenced by background soil reflectance than NDVI (Gao 1996). Overlapping NDWI of charcoal and non-forest sites may indicate that charcoal sites have similar soil moisture content as non-forest sites (Appendix Fig. A3), likely because both lack canopy cover that contributes to moisture retention in these tropical regions. Interesting, soil moisture in charcoal sites may also have been affected by remaining charcoal pieces, which may have had considerable effect on soil moisture availability (Ayodele *et al* 2009). For example, charcoal enhances moisture retention by 45% in sandy soils and decreases it by 20% in clay soils (Ayodele *et al* 2009). As we mainly observed sandy soils during our field campaign, soil moisture may have been increased by left over charcoal pieces, which may explain the slightly higher NDWI in charcoal than for non-forest sites.

Other important inputs for the Sentinel-2 classifier were NBR, Band 2 (Blue) and 11 (SWIR) (Appendix Table A3), where the NBR identifies burned areas (Rasul *et al* 2018) (Appendix Fig. A4), Band 2 the health of vegetation and closeness of the canopy (Appendix Fig. A8) (Gitelson *et al* 2002, Zhang *et al* 2013), and Band 11 vegetation water and soil moisture content (Swathandran and Aslam 2019, Tucker 1980, Ustin *et al* 2004) (Appendix Fig. A8). The importance of NBR for charcoal site detection is in line with our hypotheses and the expectation of Nakalema (2019) that indices that measure soil properties, including NBR, could aid in the detection of kiln scars. Like for NDWI, NBR mainly aids the Sentinel-2 RF classifier in distinguishing forest sites from charcoal and non-forest sites (Appendix Fig. A4), indicating that it distinguishes healthy forest stands from burned areas in charcoal sites and non-forest sites (e.g., burned agricultural land). Band 2 is most important in the detection of non-forest sites, which is exemplified by the relatively low overlap in Band 2 reflectance between non-forest sites and charcoal and forest sites (Appendix Fig. A8). This indicates that Band 2 aids the Sentinel-2 RF classifier in differentiating non-forest sites from charcoal and forest sites (i.e., differentiation between bare and vegetated land), rather than picking up signals from the harvesting area. Finally, Band 11 detects vegetation and soil moisture content, where SWIR is low in high vegetation and soil moisture conditions (Swathandran and Aslam 2019). Like for NDWI, Band 11 mainly distinguishes forest sites from charcoal and non-forest sites (Appendix Fig. A8), indicating that Band 11 allows the Sentinel-2 RF classifier to differentiate healthy vegetation in forest sites from vegetation and soil with low moisture content in charcoal and non-forest sites, respectively. This further highlights that the Sentinel-2 RF classifier differentiates kilns/kiln scars and their surrounding area from forest stands, which is in line with our original expectation. The large overlap of indices (Appendix Fig. A4) and important bands (Appendix Fig. A8) between charcoal and non-forest sites indicates challenges in the differentiation between charcoal and non-forest sites, which may explain over-prediction of charcoal sites by the Sentinel-2 RF classifier in villages without a harvesting plan because these villages exhibit many clear cutting and mixed cutting areas, where forest cover has been removed.

Like for the Landsat-8 classifier, NDVI is mainly important for the separation of forest and non-forest sites, with limited difference in NDVI between forest and charcoal sites. This may relate to the timing of acquisition of the Sentinel-2 image used in this study, which was obtained during the dry season when miombo trees shed their leaves (Vinya *et al* 2018). We chose this image date to ease the detection of the charcoal kilns, as we expected that canopy cover would interfere less with the detection of kilns/kiln scars in this period. However, it might be that other periods, such as after the appearance of grasses in charcoal sites but before leaf shedding (Cho and Ramoelo 2019) are more suitable for charcoal site detection. Future studies on charcoal site detection may examine this effect by acquiring field data and selecting satellite imagery during other periods. Besides NDVI, BSI is also of limited importance to the Sentinel-2 RF classifier, which contrasts with our expectation that the classifier may detect bare soil surrounding charcoal kilns (Iiyama et al., 2017; Woollen et al., 2016). Similarly to NDWI and NBR, BSI distinguishes charcoal, forest and non-forest sites, but the BSI of charcoal and non-forest sites almost completely overlaps, likely because charcoal kilns are located on bare soil. Hence, NDWI and NBR allow for better differentiation between classes than BSI, which explains the limited role of BSI in the classification process.

Interestingly, many bands and indices are of little importance to the Sentinel-2 classifier, as shown by limited differences in Mean Decrease Accuracy and Mean Decrease Gini. This contrasts with the Mean Decrease Accuracy and Mean Decrease Gini results of the Landsat-8 classification, which shows large differentiations in importance between input variables. This may potentially indicate that the Sentinel-2 RF classifier picks up signals from multiple features of charcoal sites, including the kiln(s)/kiln scar(s), the surrounding bare soil and the harvesting area. This partly contrasts with our hypothesis that the Setninel-2 RF classifier only detects kilns/kiln scars and surrounding bare soil. The combined detection of signals of kiln scars and surrounding bare soil in clear cutting areas and signals from harvesting areas in mixed cut areas by the Sentinel-2 RF classifier, may explain over-prediction of charcoal sites in villages without a harvesting plan. Nevertheless, we observe that the Sentinel-2 classifier mostly detects signals from harvesting areas in clear cutting areas, which have lost most of their canopy cover, which is in line with our expectation that Sentinel-2 mostly picks up signals from soil without canopy cover inference.

### *4.2 Charcoal kiln detection based on VHR data*

As expected, the visual imagery inspection method of Sedano et al. (2016) performed better in clear cut areas than in selectively cut areas because canopy cover prevented the visual observation of kilns/kiln scars in selectively cut areas. Therefore, our results highlight that visual inspection should only be used in areas where clear cutting for charcoal production occurs. Overestimation of visually inspected kilns/kiln scars may occur due to confusion of charcoal kilns with burned forest areas or livestock farms (Appendix Fig. A7), or with other features that originate from agricultural practices, such as sugarcane piles (Appendix Fig. A11). Mismatches between visually observed kilns/kiln scars and charcoal site classification outputs could be due to observer misinterpretation of features on the VHR imagery or mismatches between the timing of the VHR imagery on which charcoal kilns/kiln scars were detected and the satellite imagery used to classify charcoal sites. For instance, we visually observed kilns/kiln scars on imagery from 2017, 2019 and 2020, while we only classified charcoal sites on imagery of the year 2019. Besides this, mismatches may have occurred due to differences in spatial resolution (e.g., the 2019 VHR data examined in Google Earth has a resolution of 2 m, which differs substantially from the 0.6 m resolution and 0.5 m resolution of the 2017 Worldview-2 data, and the 2020 Planet data), or the continued visibility of kiln scars over time (Fig. 5), which may have resulted in the identification of kilns from different years than those in charcoal sites detected through classification (Oguntunde *et al* 2008, Gómez-Luna *et al* 2009).

We find that the performance of visual inspection depends on the timing of acquisition of inspected VHR images. For instance, the Worldview-2 image of 2017 was taken after the dry season when the majority of trees had lost their leaves, limited vegetation grew and contrast between soil types was low, causing difficulties in kiln (scar) detection. In comparison, the CNES image of 2019 was acquired in the wet season and leaves were present on the trees, resulting in greater contrast between soil types and abundant green vegetation. Therefore, we were better able to visually detect kilns/kiln scars on this image. It is possible that grass and other vegetation overgrowing kiln scars may have inhibited us from detecting kiln scars visually, hiding them from sight in the wet season (Sangeda and Maleko 2018). However, plant growth on kiln scars does not occur for many years, likely due to heat stress (Myonga 2019), which affects soil physical and chemical properties and microbes living in the soil (Gómez-Luna *et al* 2009). For instance, previous researchers only found vegetation on 10% of charcoal kiln scars they monitored in Kilosa district (Sangeda and Maleko 2018), making it unlikely that vegetation growth on kiln scars during the wet season affects the ability to observe them. Finally, we mainly observed mismatches between the classification output and visually inspected kilns/kiln scars in agricultural areas, likely because we mainly collected data on charcoal sites in forested areas. Hence, our test and training data contained limited locations of kilns/kiln scars on agricultural land. The experienced variations in visual imagery detection performance suggests that more detailed studies are necessary to improve our understanding of the impact of VHR satellite image acquisition timing on charcoal site detectability. Meanwhile, visual inspection of VHR satellite imagery could be combined with automated methods to increase the robustness of charcoal site recognition in forested areas, and to provide test and training data for automated classification methods.

### *4.3 Robustness of charcoal site detection*

The large size of the area classified as charcoal site likely results from the relatively lower user accuracy for charcoal site prediction (78.91% for Landsat-8 classification and 83.56% for Sentinel-2 classification) than for forest and non-forest site prediction (Table 2 and 3, respectively), which causes over-prediction of charcoal sites. Based on this finding, we caution against the use of a single classification method to classify charcoal sites, and recommend that scientists, policy makers and practitioners use a combination of methods to improve reliability of charcoal site classification. We show that the combination of two RF classification outputs takes advantage of signals from all features of charcoal sites, namely the harvesting area for charcoal production, the kiln (scar) and the surrounding bare soil. While the Landsat-8 classifier discriminates better between charcoal sites and non-forest sites because it detects the phenology and greenness of the vegetation in harvesting areas (see Section 4.1.1), the Sentinel-2 classifier discriminates better between charcoal and forest sites because it better detects a loss of soil moisture and canopy moisture at the kiln (scar) and in the surrounding area (see Section 4.1.2). Hence the combination of the two methods likely removes part of the over-prediction occurring in each of the individual methods, as shown by our robustness analysis. Therefore, the chance that a charcoal site is identified in areas with maximum classification robustness is higher than in those with lower than maximum classification robustness, as classification uncertainty is lower in these areas.

The combination of three methods allowed us to identify charcoal sites with a higher precision than that achieved by each of the methods separately because it reduces variation in charcoal site predictions across methods. We find relatively large differences in the extent of high robustness charcoal sites (0.06% of our study area after cloud removal), medium (5.87% of our study area after cloud removal), and low (23.43% of our study area after cloud removal). These fractions are in line with our expectations that the high robustness area relatively conservatively predicts charcoal sites, and thus covers a relatively small area compared to medium and low robustness sites. We believe that it is unlikely that charcoal production takes place in all identified low robustness sites because (i) charcoal sites, including their harvesting area are relatively small, in particular in selectively cut areas, (ii) harvesting areas are scattered across the landscape (Sedano *et al* 2020a), and (iii) charcoal sites are intertwined with relatively undisturbed forest or forest that is disturbed by other drivers of forest degradation and deforestation (e.g., small fires and livestock farms) (Sawadogo *et al* 2002). In contrast, we expect that extent of the high robustness areas is quite conservative and limited by the number of sites we can monitor on the ground or with VHR imagery, as canopy cover inhibits detection of kilns (see Section 4.2). Nevertheless, high robustness sites still reflect areas with lowest variability in charcoal site recognition, where the chance that charcoal sites are present is highest. Therefore, the true estimate of charcoal production likely lies somewhere between the area extent of the high and the medium robustness sites.

Overall, we are confident that our combined method can robustly distinguish charcoal sites under different harvesting regimes. Although maps of medium to high robustness charcoal sites may not be suitable to determine the exact extent of charcoal production, they can be used to identify those areas with the highest chance that charcoal production has taken place. This allows for impact assessments of the effects of charcoal production on forests and ecosystem services, e.g., by assessing biomass and biodiversity changes in a subset of medium robustness charcoal sites with high classification robustness. Medium to high robustness charcoal maps may also be utilized to test compliance with existing harvesting plans because we find differences in charcoal site patterns between villages with and without a harvesting plan (Fig. 7). Finally, active monitoring of high to medium robustness charcoal sites may shed light on general spatiotemporal changes in charcoal production in response to varying harvesting regimes, e.g., by comparing charcoal production in areas with and without harvesting plan and its impact on forest extent, degradation and biodiversity. Hence, estimations of the exact extent are not necessary for many applications

### *4.4. Effects of canopy cover on charcoal site detection*

The relatively low percentage of pixels with maximum classification robustness out of all pixels classified as charcoal site by the Landsat-8 and Sentinel-2 RF classifiers (Fig. 7), as well as the limited kilns/kiln scars detected in villages with a harvesting plan, indicates that canopy cover disrupts both charcoal site classification and the visual imagery inspection of kilns/kiln scars. While not surprising, this challenges the detection of selectively cut charcoal sites, even with a combined method approach. This finding is in line with studies that attempt to detect understory vegetation (Tuanmu *et al* 2010) and other features located underneath the canopy. However, these results can also be confounded by the relatively higher cloud coverage in villages with a harvesting plan than those without on the Sentinel-2 image used in this study (Appendix Fig. A1), as we removed those areas that exhibited cloud coverage (see Section 2.6). Overall, we observe a lower classification robustness along the edges of maximum classification robustness charcoal sites, in particular in selectively cut areas, which was expected as these areas mark the boundary between land-cover classes. We reduce some of the effects of canopy cover by only selecting pixels classified as charcoal site 100% of the time, which resulted in ensemble maps of higher accuracy. In addition, challenges of canopy cover may be overcome by combining other types of remote sensing data known to be able to detect understory features (Santos *et al* 2018).

### *4.5 Limitations of the study*

Detection of charcoal sites is challenging because of their characteristics and dynamic nature. We find that the charcoal site spectral signature overlaps with that of other types of forest degradation. The extent to which this confusion takes place is currently unclear because tree harvesting in forests is primarily caused by charcoal production in our study area, and conversion from forest to agriculture is often accompanied by charcoal production (Ishengoma *et al* 2016). In addition, although the accuracies derived in this study are relatively high, misclassification occurs between forest, non-forest and charcoal sites, and we observe some over-prediction of charcoal sites. Therefore, results of a single classification method, using either Landsat-8 or Sentinel-2 data, in areas with selective cutting should be interpreted with caution because it is impossible to verify the presence of kilns/kiln scars through visual imagery inspection in these areas and we show that the field locations are not completely captured by the classification results in these conditions. Future studies may assess whether the RF models can be improved by including alternative vegetation indices, such as the Atmospherically Resistant Vegetation Index (ARVI) (Kaufman and Tanre 1992), which may account for atmospheric effects caused by smoke emission from kilns (Kammen and Lew 2005), release of small particulate matter when unloading charcoal kilns (Kammen and Lew 2005), and burning of agricultural fields after harvesting (Mkoma *et al* 2013), which we observed frequently during our field study. Besides this, the results of this study may be affected by test and training data partitioning and by the accuracy of the field data, although we find relatively low sensitivity to test and training data in our analyses (standard deviations between 2.40% and 2.82% for Landsat-8 and Sentinel-2 RF classifications, respectively). Overall, we recommend to combine Landsat-8 and Sentinel-2 classification outputs with uncertainty maps (in our case entropy in classification outputs) in areas where selective cutting takes place. This would allow for the production of maps that reflect a continuous measure of classification robustness to distinguish areas where the chance is highest that charcoal production has taken place. Our field data was obtained using a GPS with 5 to 10 m accuracy, which may have caused spatial mismatches between the actual locations of the kilns/kiln scars and GPS coordinates, potentially affecting which pixels were used to train the classifier. As the spatial resolution of Sentinel-2 is higher than that of Landsat-8 data, the potential impact of the GPS accuracy was likely larger for Sentinel-2. We actively tried to overcome this error by standing in the middle of charcoal kiln (or its remains) when taking GPS measurements. However, tree cover could have interfered with the GPS signal, potentially causing larger mismatches between the exact locations of the kilns/kiln scars in areas with abundant tree cover, such as in selectively cut areas. Further sources of error could be related to selecting sites through visual inspection where degradation took place due to charcoal production or other forestry activities, despite our care in selecting sites in undisturbed forest land. Although we have explicitly chosen a Sentinel-2 image acquired in the dry season, we do not know the performance of the RF classifier on Sentinel-2 imagery acquired at different times of the year. For instance, it might be that the kiln/kiln scar and surrounding bare soil contrasts more with the surrounding vegetation in the wet season, which could aid the Sentinel-2 classifier to better distinguish between charcoal, forest and non-forest sites. Different extents of cloud coverage between villages with and without a harvesting plan on the Sentinel-2 image used in this study (Appendix Fig. A1) have influenced our classification robustness results because we excluded areas exhibiting cloud coverage on the Sentinel-2 image, likely underestimating the extent of the medium robustness area in villages with a harvesting plan, where most cloud coverage occurred. As our study relies on a large field dataset, upscaling charcoal site classification may require a large field campaign, likely associated with high costs. Although Landsat-8 and Sentinel-2 data are readily available at global scales, VHR imagery availability is more restricted, in particular in the tropics, and often needs to be purchased. Fortunately, our study highlights that combining output of Landsat-8 and Sentinel-2 RF classifiers already allows for the identification of areas with maximum classification robustness, where the chance that a charcoal site is present is higher than in areas classified by a single classification method. This suggests that VHR imagery may solely be necessary to identify charcoal sites with highest robustness, which can only be achieved in clear cutting areas because canopy cover prevents detection of kilns/kiln scars in selectively cut areas. Finally, future research may assess whether our RF models may be transferable over space and time, hereby avoiding time consuming collection of data on charcoal sites in the future.

## 5. Conclusion

Because of risks of forest loss and degradation related to charcoal production there is a need for high accuracy monitoring of charcoal production to inform policy makers and managers. We show that a combined remote sensing approach allows for the detection of a wide variety of charcoal sites under different harvesting regimes and canopy cover. Combining automated random forest algorithm outputs produced with Sentinel-2 or Landsat-8, while accounting for classification uncertainty, provides robust predictions of charcoal sites even in selective cutting areas, where canopy prevents the visual detection of charcoal kilns/kiln scars. In clear cutting areas a combination of automated classification and visual inspection performs best. We believe that the enhanced performance of our combined approach is due to the varying charcoal site characteristics that each method detects; namely the phenology of the harvesting area, the kiln scar and the kiln itself. Hence, by combining methods, variation charcoal site prediction is reduced, which increases the likelihood that areas identified as charcoal site were indeed subjected to charcoal production activities (i.e., kiln building and harvesting trees for charcoal production). Even though an approach such as the one presented herein has clear advantages, scaling it to national or global assessments may require a large investment in test and training data either through in situ measurements or visual inspection of VHR imagery. This could be obviated using citizen science platforms and AI methods that rely on pattern recognition, as well as fusion with other remote sensing data and methods that measure 3D structures in the landscape.

Our results highlight ways in which remote sensing can be used to increase our understanding of charcoal production dynamics, contributing to a growing body of research that investigates the link between energy production-consumption and forest degradation. Our approach could also contribute to the monitoring of charcoal production and forest management activities, and assessments of compliance with harvesting regimes. More generally, our results provide insights in the ways remote sensing can be used to identify areas targeted by specific drivers of deforestation and forest degradation, which may ultimately pave the path to assess and monitor their individual impacts on forests, biodiversity and related ecosystems services. For instance, our combined approach may be used to detect changes in charcoal production intensity when applied over multiple years, which allows for estimates of biomass removal for charcoal production, providing fundamental information for forest managers around the world to locally track and monitor compliance with existing rules, regulations and harvesting schemes.

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## Author contributions

The author contributions are based on CRediT (Contributor Roles Taxonomy), which aims to recognize individual author contributions to facilitate collaborations and to diminish disputes among authors (https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement).

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# Chapter 5

## Understanding social-ecological processes driving charcoal production patterns at a landscape scale

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*This chapter is in progress and will be submitted to the journal Landscape Ecology following acceptance of the paper written for Chapter 4 on which the results of this paper are based*

The combined remote sensing approach developed in **Chapter 4** paves the way for **Chapter 5** of this thesis in which I use the ensemble maps of high robustness areas to assess effects of social-ecological drivers on charcoal production site patterns in the landscape for two charcoal production systems, (i) traditional open access systems, and (ii) community-based natural resources management (CBNRM). In total, I assess the impact of three social-ecological drivers on charcoal patterns (size, shape, density and distribution): aboveground biomass prior to charcoal production (i.e., resource units), travel distance to the forest (i.e., resource system) and governance (i.e., governance system). In other words, in **Chapter 5** I implement the methodology of **Chapter 4** and combine it with data on forest biomass and travel distance to provide a more detailed spatial assessment of forest use in resource systems of charcoal production systems under different governance. The results of this study may inform future modelling studies, which may be used to predict charcoal site patterns in the landscape and ultimately their implications on forest ecosystem dynamics and biodiversity.

**Figure 5.1** provides an overview of the social-ecological system components assessed in **Chapter 5**, their interactions, and the specific charcoal production systems compared. The **Supplementary Materials** of **Chapter 5** can be found in the **Appendix of Chapter 5** of this thesis.

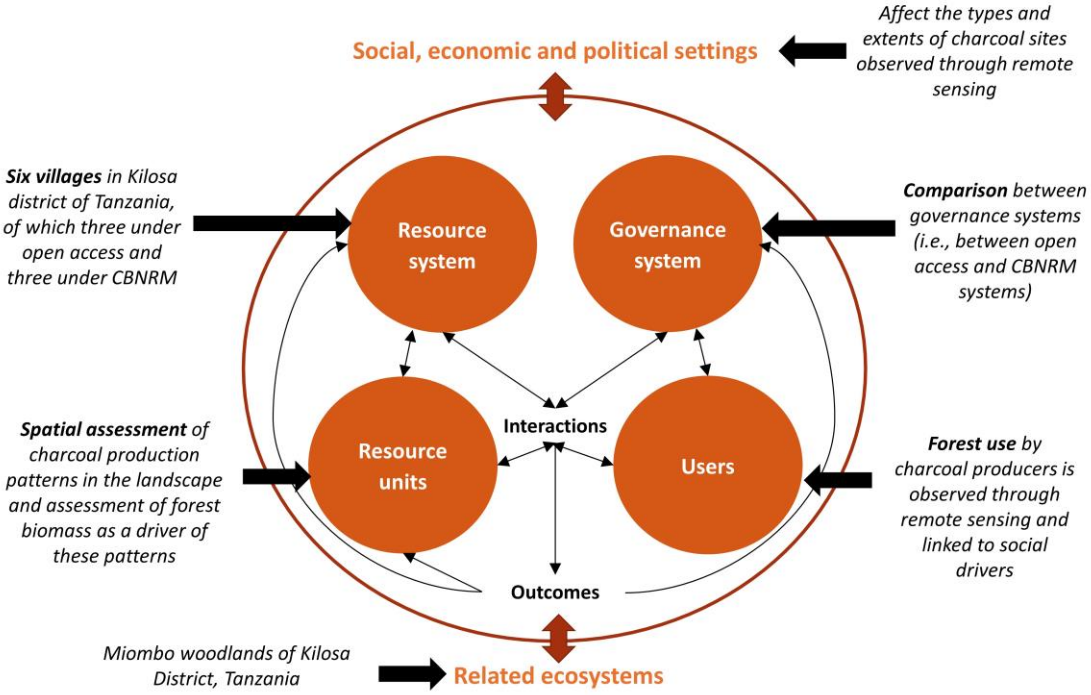

**Figure 5.1** The social-ecological system components assessed in **Chapter 5**, their interactions, and the specific charcoal production systems compared. CBNRM = community-based natural resources management.

Scientific paper in progress

# Understanding social-ecological processes driving charcoal production patterns at a landscape scale

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## Abstract

Charcoal provides important energy for hundreds of millions of people but simultaneously contributes to 7% of global deforestation and forest degradation, which produces patterns of charcoal sites throughout the landscape. To effectively assess and eventually predict charcoal-related impacts on forests, a better understanding of the ways in which interrelated social-ecological drivers influence these charcoal production patterns is warranted. In this study, we use remote sensing to empirically compare charcoal site patterns (size, shape, density and distribution) in six Tanzanian villages, in response to one ecological and two social drivers, namely (i) biomass availability, (ii) travel distance to these resources, and (iii) forest governance (e.g., rules and regulations). We find corresponding peaks in charcoal site numbers and sizes and biomass at specific distances from village centers (at 2-6 km and 4-7 km) in three study villages where charcoal producers limitedly adhere to existing rules and regulations, indicating combined effects of biomass availability and travel distance. In contrast, we find significantly smaller and more regularly shaped charcoal sites and no corresponding peaks in charcoal site patterns and biomass with distances from village centers in three study villages with a participatory harvesting plan in place, indicating a potential for governance to shape charcoal production patterns. Nevertheless, we found only 9.72 to 16.04% of charcoal sites inside designated areas for production in these villages, highlighting remaining challenges in enforcement under participatory management. Overall, we provide a first time insight in interacting effects of social-ecological drivers on landscape patterns of forest use for charcoal production.

**Keywords** Charcoal · forest biomass · social-ecological systems · landscape patterns · remote sensing

## 1. Introduction

Charcoal is an important biomass-based renewable energy for cooking and industry (FAO 2017). Currently, charcoal production causes a large fraction of forest degradation, as well as 7% of deforestation worldwide, resulting in a loss of forest-related ecosystem services, such as biodiversity, soil stability and carbon stocks (Chidumayo and Gumbo 2013). Hundreds of millions of people in the tropics rely on charcoal as an energy source, and over 40 million people are employed in the charcoal value chain (FAO 2017). Negative impacts of charcoal production on forests are expected to continue because of a predicted 5% growth in charcoal production by 2100 (Santos *et al* 2017), in particular upon a continuation of unregulated production (Iiyama *et al* 2017, Sola *et al* 2021, Schure *et al* 2013, Ruuska 2013). Current charcoal production practices produce landscape patterns that consist of charcoal production sites of different sizes, shapes and densities (Sedano *et al* 2016, 2021). These patterns are influenced by a range of social-ecological drivers, including forest biomass availability (Ahrends *et al* 2010, Silva *et al* 2019), tree community composition (Kumapley and Dumevi 2016, Malimbwi *et al* 2005, Tabuti *et al* 2003), distance to village centers and roads (Baumert *et al* 2016, Sedano *et al* 2016), as well as governance that prescribes harvesting plans that dictate the size, density and distribution of charcoal production sites (Ishengoma *et al* 2016). The landscape pattern that emerges from charcoal production sites in turn determines the overall extent and intensity of forest loss and degradation (Sedano *et al* 2016, 2021), and ultimately the effect of charcoal production on ecosystem services (Woollen *et al* 2016, Vollmer *et al* 2017), biodiversity (Kalaba *et al* 2013, Kouami *et al* 2009, Naughton-Treves *et al* 2007) and livelihoods (Enbakom *et al* 2017, Kutiote *et al* 2019). Yet, variability in charcoal site spatial characteristics challenges the assessment of its spatiotemporal ecological and landscape implications. Hence, there is a need for a comprehensive assessment of the effects of social-ecological drivers on charcoal production patterns in the landscape in order to better assess and predict effects of charcoal production on forest resources and biodiversity (Ghilardi and Mas 2011, Ghilardi *et al* 2018).

Generally, charcoal production sites include one or multiple kilns (i.e., carbonization ovens used for charcoal production), or kiln scar(s) (i.e., remains of the carbonization ovens). Around the kiln(s) or kiln scar(s) trees are harvested for charcoal production, which produces a harvesting area (Sedano *et al* 2016). Kilns, kiln scars and harvesting areas all differ in size and shape (Sedano *et al* 2020a, Silva *et al* 2019). For instance, a recent field study in Mozambique found that kilns have an average length of 8.1 (ranging between 2 and 26 m), an average width of 2.2 m ± 0.3 m, and an average height of 1.2 m ± 0.2 (Sedano *et al* 2016). The kilns were surrounded by an average cutting are of 0.31 ha ± 0.28 ha (Sedano *et al* 2016). Together the charcoal production sites of varying sizes, shapes densities and distributions produce a landscape pattern in response to a range of interacting social and ecological drivers (Sedano *et al* 2016, 2021). An ecological driver is the availability of aboveground biomass for charcoal production, in particular in the form of suitable trees for charcoal production, which tend to be dense timber trees that produce charcoal of high calorific value (Sedano *et al* 2016). Hence, charcoal producers make choices on the location and potentially the size and shape of the charcoal sites they create based on aboveground biomass availability. A social driver is travel distance to forests to produce charcoal. For instance, recent studies found both a gradual increase in the density of kilns in the landscape close to roads and centers of demand and a gradual shift outwards into the forest, likely driven by a reduction of available forest biomass over time to such extent that it becomes more valuable for charcoal producers to produce further away (Ko *et al* 2011, Baumert *et al* 2016, Sedano *et al* 2016, 2021).

Charcoal production site patterns in the landscape may further be influenced by forest governance regimes (Schure *et al* 2013, van 't Veen *et al* 2022). We define governance regimes as the ways in which governing bodies, such as local and regional governments, interact with each other to negotiate, make and enforce decisions regarding forest use and conservation. At present, charcoal production is mainly carried out under open access, where producers relatively freely harvest forest resources to produce charcoal because of limited adherence to existing rules and regulations. This largely prevents existing governance regimes from influencing production practices (Schure *et al* 2013, van 't Veen *et al* 2022), and may, at high levels of charcoal demand, result in overexploitation of forest resources with risk of depletion (van 't Veen *et al* 2021). In an attempt to regulate charcoal production, transitions in governance regimes are initiated, such as transitions to community-based natural resources management (CBNRM), which has the aim to empower communities to manage their forests through a communal decision-making process (e.g., following the implementation of CBNRM projects by external NGOs in Tanzania and Senegal) (van 't Veen *et al* 2021). Transitions in governance may affect the size, shape, density and distribution of charcoal production sites in the landscape. For instance, under CBNRM a harvesting plan may be implemented that specifies a harvesting regime for charcoal production. Such harvesting plan may, for instance, indicate the designated forest area where charcoal producers are allowed to produce charcoal, the size of the harvesting areas of charcoal sites (e.g., 50 m harvesting blocks), and the distribution of these harvesting areas throughout the landscape (e.g., in a checkerboard pattern) (Ishengoma *et al* 2016). If charcoal producers follow all laws, rules and regulations for charcoal production specified in a CBNRM harvesting plan, charcoal production patterns in the landscape should largely be dictated by governance rather than other social-economic drivers.

Patterns of charcoal sites that form throughout the landscape as a result of social-ecological drivers affect forest biomass and tree community composition (Ding *et al* 2012, Gatti *et al* 2015). The extent of these effects depends on both the spatial distribution of harvesting areas for charcoal production (Sedano *et al* 2016, 2020a, 2021), the purpose of charcoal production (Iiyama *et al* 2017), the manner in which charcoal is produced (Chidumayo and Gumbo 2013, Gatti *et al* 2015, Kouami *et al* 2009, Wurster 2009), and the type of forest it is produced in (Sangeda and Maleko 2018). First, research suggests that the spatial pattern of tree harvesting can affect biodiversity more than the intensity of tree removal because of the fragmentation it produces in the landscape (Maleki *et al* 2021). Second, charcoal may be produced as final product to provide energy to urban centers (Sedano *et al* 2016) and industry (Piketty *et al* 2009), or it may be produced as a by-product to convert forest land into agricultural land (Iiyama *et al* 2017). Charcoal as a by-product for agriculture produces largest impacts on forest biomass and biodiversity because it results in (permanent) deforestation (Colón and Lugo 2006). Third, charcoal produced for the purpose of energy consumption may be produced through clear cutting, meaning the removal of all trees in the harvesting area, or through selective cutting, meaning the removal of specific trees based on preference or rules. Charcoal produced through clear cutting causes high initial biodiversity loss, soil erosion and seedling mortality (Huth and Ditzer 2001), leaving behind barren land that takes a long time to recover (Chidumayo and Gumbo 2013, Fearnside 1989). This, despite its high regeneration potential related to high light availability upon canopy removal (Chidumayo 2004). In contrast, selective cutting practices leave behind land that remains largely covered by vegetation, and causes less initial biodiversity loss and erosion than clear cutting (Gatti *et al* 2015, Wurster 2010). Nevertheless, these effects may still be substantial (Kouami *et al* 2009). Finally, the regeneration of biomass and biodiversity varies between forest types, e.g., fast growing forest types like tropical dry forests regenerate faster through coppicing (Sangeda and Maleko 2018).

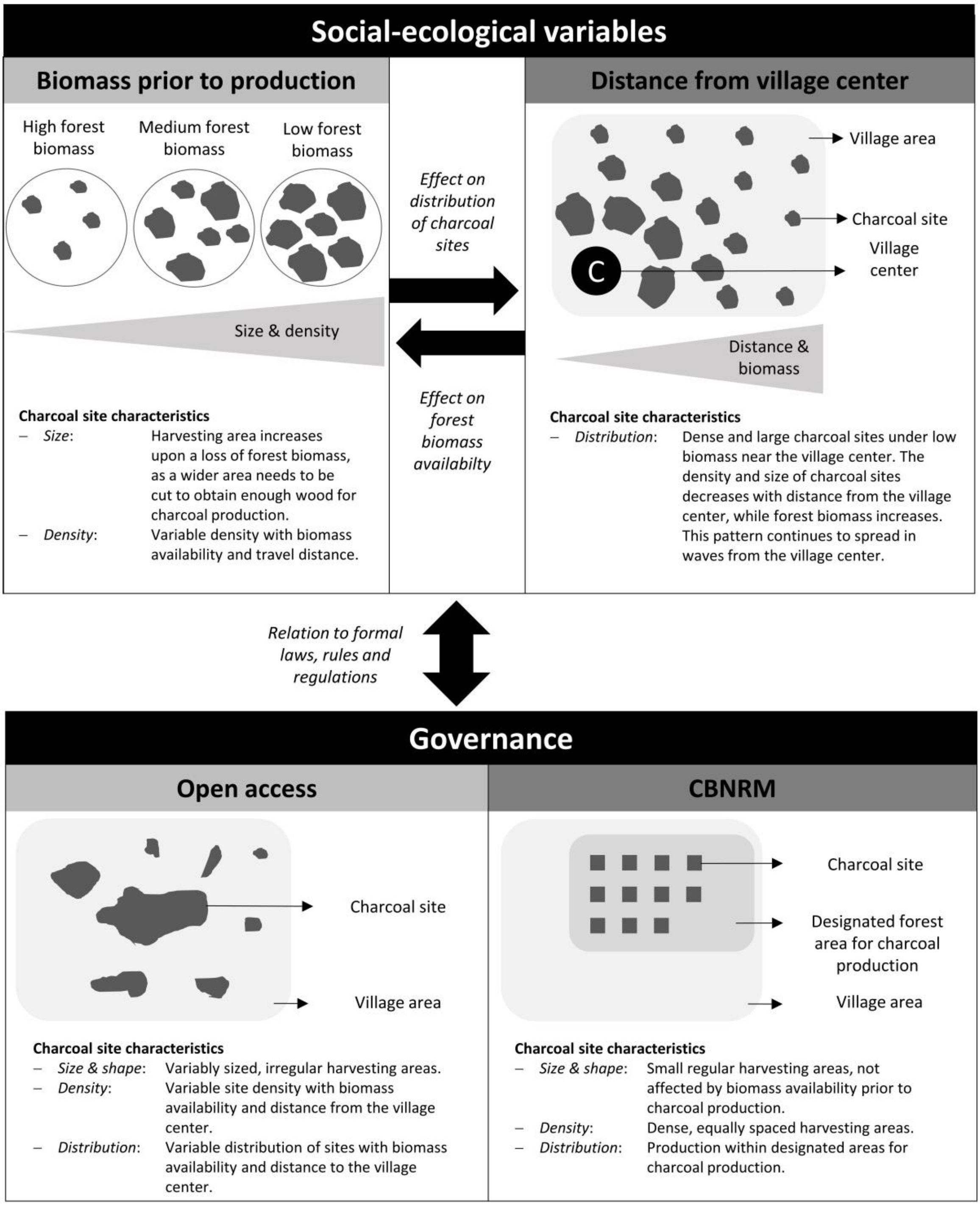
In this study, we use a remote sensing approach to map charcoal production sites in the landscape and examine (i) effects of biomass availability prior to charcoal production on landscape patterns of production sites (size, shape, density and distribution) and (ii) whether social factors (travel distance and forest harvesting plans) influence them. To do so, we compare charcoal production systems under two different governance systems: open access and CBNRM systems. First, we hypothesize that biomass availability prior to charcoal production influences harvesting area sizes because charcoal producers need to harvest larger areas when forest biomass is low and smaller areas when forest biomass is high to obtain the same resources for charcoal production (Fig. 1). We hypothesize that charcoal sites are generally irregular in shape because charcoal producers have to obtain sufficient biomass to produce charcoal, which is a function of available biomass and the distribution of suitable tree species in the landscape. Second, we hypothesize that distance from village centers affects patterns of charcoal sites throughout the landscape because charcoal producers tend to use forest biomass sources closer to their residencies first but over time move further away as closer resources become depleted (Malimbwi *et al* 2005, Schaafsma *et al* 2014, Vollmer *et al* 2017). Thus, we expect a dense distribution of charcoal sites near village centers and more scattered charcoal sites further way from village centers. Finally, we hypothesize that charcoal producers operating under CBNRM follow all laws, rules and regulations for charcoal production specified in the harvesting plan; hence we expect governance to be the main driver of charcoal patterns under this governance system.

## 2. Methods

### *2.1 Study area*

This study was conducted in six villages in Kilosa district, Tanzania, located approximately 300 km east from Dar es Salaam city (Fig. 2). All villages contain miombo woodland, a type of tropical dry forest dominated by *Brachystegia bohemii*, *B. spiciformis*, *B. microphylla*, *Combretum* spp., *Albizia* spp., and *Commiphora* spp. (Ishengoma *et al* 2016). Precipitation in Kilosa district ranges between 800 and 1200 mm annually and falls in two rainy seasons, with a short rainy season between November and January and a longer rainy season between March and May (Ishengoma *et al* 2016). Temperature is on average 25 °C and ranges from 19 to 30 °C (Ishengoma *et al* 2016). In our study villages, elevation ranges between 411 and 1325 m (estimated using a 30 m resolution elevation map for Tanzania from The Shuttle Radar Topography Mission data from the SERVIR AFRICA team and NASA from 2018 (https://www2.jpl.nasa.gov/srtm/tanzania.htm, last entered March 2nd 2022)).

The six villages in our study area differed in governance regime, charcoal production intensity, and the type and extent of forest cover. Three of the villages participated in the Transforming Tanzania's Charcoal Sector (TTCS) project, a CBNRM project of the Tanzania Forest Conservation Group (TFCG) (Ishengoma *et al* 2016). From now on we refer these villages as CB-villages*.* In CB-villages charcoal was produced in a designated forest area, called a Village Land Forest Reserve (VLFR), in accordance with a participatory harvesting plan. The harvesting plan specified the amount and manner of charcoal production; production takes place in a designated forest area in which producers are allowed to harvest blocks of 50x50 m in specified years, following a checkerboard pattern. Within the designated area, trees within 60 m from water bodies, trees with a diameter at breast height below 15 cm and timber tree species should remain uncut (for a detailed description of the harvesting plan see Ishengoma et al. (2016)). Hence, upon compliance to the harvesting plan of CB-villages, a substantial number of trees should remain present in the harvesting area following charcoal production. Because the remaining three study villages do not have a specific harvesting plan in place, charcoal production occurred illegally in these villages. Therefore, we considered the governance system in these villages open access and referred to them as OA-villages. As one of the OA-villages only recently got the status



**Charcoal site characteristics** (Biomass prior to production)

- *Size*: Harvesting area increases upon a loss of forest biomass, as a wider area needs to be cut to obtain enough wood for charcoal production.
- *Density*: Variable density with biomass availability and travel distance.

**Charcoal site characteristics** (Distance from village center)

- *Distribution*: Dense and large charcoal sites under low biomass near the village center. The density and size of charcoal sites decreases with distance from the village center, while forest biomass increases. This pattern continues to spread in waves from the village center.

**Charcoal site characteristics** (Open access)

- *Size & shape*: Variably sized, irregular harvesting areas.
- *Density*: Variable site density with biomass availability and distance from the village center.
- *Distribution*: Variable distribution of sites with biomass availability and distance to the village center.

**Charcoal site characteristics** (CBNRM)

- *Size & shape*: Small regular harvesting areas, not affected by biomass availability prior to charcoal production.
- *Density*: Dense, equally spaced harvesting areas.
- *Distribution*: Production within designated areas for charcoal production.

**Figure 1.** Conceptual framework of expected charcoal site spatial patterns in the landscape under different governance regimes (i.e., open access and community-based natural resources management (CBNRM)).

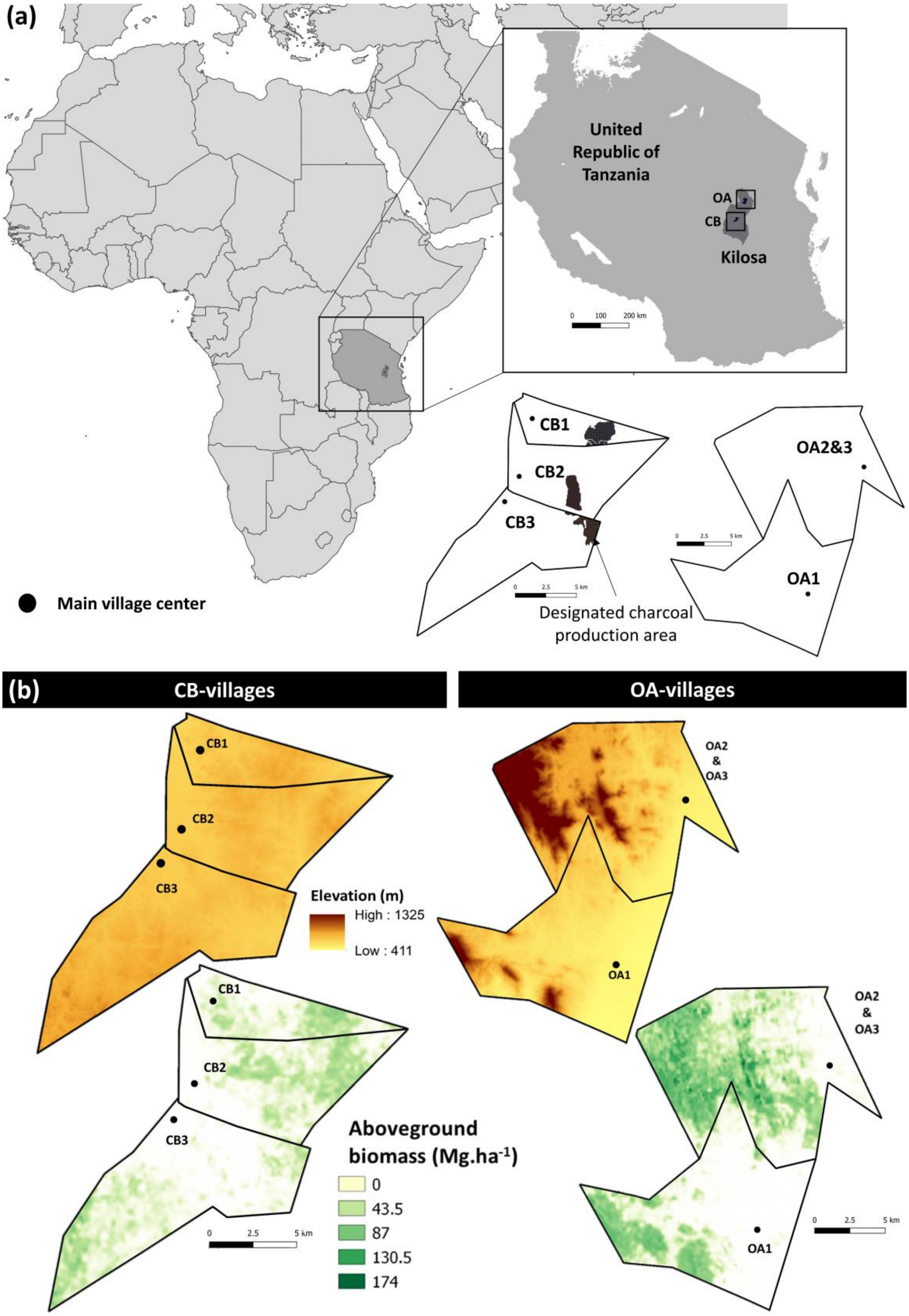


**Figure 2.** We conducted our study in six villages in Kilosa district of Tanzania. Three villages participated in the community-based natural resources management (CBNRM) project, Transforming Tanzania's Charcoal Sector (TTCS), of Tanzania Forest Conservation Group (TFCG). We refer to these villages as CB-villages. The other three villages are under open access, and we refer to these villages as OA-villages. We consider only two OA-villages because one OA-village (OA3) has only recently received the status of village by the Tanzanian government and falls within the extent of the shapefile boundary of OA2. Hence we refer to this village as OA2&3. Panel (a) shows the study area including designated areas for charcoal production in CB-villages, and panel (b) show aboveground biomass availability for the year 2017 in Mg.ha$^{-1}$ as well as elevation in m in the study area.

of village (OA3), the exact boundary of this village had not yet been determined. Instead, this village was imbedded in the boundary of another OA-village (OA2). Thus, we compared three CB-villages with two OA-villages, of which one is a single OA-village and the other one a conglomerate of two OA-villages, which we referred to as OA2&3.

The total area of CB-villages is 157.8 km$^2$ and the total area of OA-villages is 247.9 km$^2$. Hence, the studied area covered by OA-villages is approximately 1.6x larger than the area covered by CB-villages. Elevation differs between OA-villages and CB-villages; it ranges between 411 and 1325 m in OA-villages and between 489 and 707 m in CB-villages.

### *2.2 Data collection*

We used two types of data in this study, namely (i) maps of charcoal sites for the year 2019 (30 m resolution), and (ii) aboveground biomass maps for the year 2017 (100 m resolution), both covering our entire study area. We defined charcoal sites as those sites with one or multiple kilns or their scar (s) and a surrounding harvesting area, where trees were cut for charcoal production. The charcoal site maps were derived from a previous study for which we developed a combined remote sensing approach with Landsat-8 and Sentinel-2 data to predict charcoal sites for the year of 2019 with high robustness (see Chapter 4 for details) (van 't Veen *et al* in review). In that study, we classified our study area into three classes, namely (i) charcoal sites, (ii) forest sites, and (iii) non-forest sites, using Landsat-8 and Sentinel-2 data, respectively. We produced two high accuracy classification maps (one for Landsat-8 and one for Sentinel-2 data) and compared the classification results with field locations of charcoal sites and visually inspected charcoal sites on very high-resolution (VHR) satellite imagery. Then, we combined the two classification maps to derive a map of pixels that both the Landsat-8 and Sentinel-2 classifiers identified as charcoal sites. We considered these areas charcoal sites of high classification robustness; the areas where the chance is highest that charcoal production has occurred. In this study, we used our map of high classification robustness charcoal sites to assess charcoal site patterns in the landscape.

We downloaded aboveground biomass data from European Space Agency (ESA) through the Climate Change Initiative's Open Data Portal (https://climate.esa.int/en/odp/#/dashboard, last visited on the 5th of August, 2021). The data was generated as part of ESA's Climate Change Initiative Biomass Project and provides estimates of aboveground biomass in Mg.ha$^{-1}$. We used aboveground biomass data for the year 2017 rather than 2018 to assess aboveground biomass prior to charcoal production. This, to avoid that some of the charcoal sites recognized through our combined remote sensing method could have originated from charcoal sites created in 2018, rather than in 2019. We believe that detection of charcoal sites originating from 2017 would have been less likely upon remotely sensing 2019 satellite imagery, as two years of regrowth after production alters the spectral signal of charcoal sites (Sedano *et al* 2020a, 2020b). Therefore, we believe that the aboveground biomass data of 2017 provides the most suitable data to evaluate the influence of forest aboveground biomass availability on spatial patterns of charcoal sites.

We used a shapefile of the village boundaries and the designated areas for charcoal production to clip data to the extent of our study villages and to assess differences in charcoal production extent between designated areas for charcoal production and remaining village land. The shapefiles were provided to us by TFCG and are available upon request.

### *2.3 Calculating landscape metrics*

We used the charcoal site map of 2019 to quantify the spatial patterns of charcoal sites, including their size, shape and density. We defined the size of charcoal sites as the size of their harvesting area (in ha), the shape as the harvesting area shape (unitless), and charcoal patch density as the distance between charcoal patches within a given area (in m). We assessed these variables using patch metric functions of the "landscapemetrics" package in R (Hesselbarth *et al* 2021), namely patch area (area), patch shape (shape), and Euclidean nearest-neighbor distance (enn). Although other patch metrics than area, shape and enn were available, such as the core area index, we did not include them because they are heavily correlated with each other (Appendix Fig. A1) and, therefore, do not add more valuable information to assess the impact of social-ecological drivers on charcoal production site characteristics. We used the area, shape and enn patch metrics because these provided the most straightforward information about the charcoal site pattern characteristics of interest. Table 1 provides a description of each patch metric calculated in this study, their formula and a rationale for including the metric in our analysis. We calculated the landscape metrics for each study village area. To assess effects of distance to village centers on the metrics, we also calculated the metrics for consecutive buffers of 200 m width around the main village center outwards.

**Table 1.** Patch metrics used to quantify the spatial characteristics of charcoal sites, a rationale for their inclusion, and their formula.

| **Metric** | **R-function** | **Description & rationale for inclusion** | **Formula** |
|---|---|---|---|
| *Patch area (area)* | lsm_p_area | ❖ Description: Measures the total area of each patch within a given area in hectares (ha).<br>❖ Rationale: We hypothesize that the size of charcoal sites is more variable in OA-villages than in CB-villages (Fig. 1) because we expect charcoal sites in OA-villages to increase in area with a decrease in biomass, as charcoal producers would need to harvest a larger area at low biomass levels to derive the same amount of wood for charcoal production. In CB-villages, we expect charcoal producers to follow the CBNRM harvesting plan. Therefore, we only expect small charcoal sites of about 50x50 m (0.25 ha) in CB-villages, which cover approximately one grid cell of our 30 m resolution charcoal site map. | $AREA = a_{ij} * (\frac{1}{1000})$<br>, where $a_{ij}$ is the patch area in square meters ($m^2$). Patch area is measured in hectares (ha). |
| *Patch shape index (shape)* | lsm_p_shape | ❖ Description: A measure of the compactness of a patch, i.e., the smaller the patch shape, the more compact a patch is. It is calculated by dividing the actual perimeter of each patch by the minimum perimeter they could have based on the number of cells the patch encompasses.<br>❖ Rationale: We hypothesize that charcoal producers in OA-villages produce charcoal in harvesting areas of irregular shape because we expect these producers to respond to the availability of aboveground biomass, species composition and landscape features, such as hills and mountain slopes, when shaping their harvesting area. We hypothesize that charcoal sites are more compact in CB-villages than in OA-villages because charcoal producers are expected to adhere to CBNRM harvesting plan regulations that specify a squared 50 m harvesting area. | $SHAPE = \frac{p_{ij}}{\min p_{ij}}$<br>, where $p_{ij}$ is the perimeter of the patch measured in cell surfaces and *min* $p_{ij}$ the minimal perimeter the patch could have measured in cell surfaces. The patch shape index is unitless. |
| *Euclidean nearest-neighbor distance (enn)* | lsm_p_enn | ❖ Description: This metric measures the distance between a patch and the patch of the same class nearest from it. It is often used as a measure of patch isolation from other patches. The smaller the Euclidean nearest-neighbor distance, the more densely distributed charcoal patches are.<br>❖ Rationale: We expect a more concentrated density of charcoal sites closer to settlements and a more dispersed density further away in OA-villages because we expect producers to harvest aboveground biomass close to the village center first and move further away when aboveground biomass reduces over time as a result of charcoal production. In CB-villages, we expect to see high density of charcoal sites in the 50 m forest harvesting blocks inside of the designated area. We do not expect charcoal production sites outside of the designated area for charcoal production in CB-villages. | $ENN = h_{ij}$<br>, where *hij* equals the distance to the neighboring patch of the same class that is closest to the patch. The Euclidean nearest-neighbor distance measures the distance between patches from edge to edge. The Euclidean nearest-neighbor index is calculated in meters (m). |

### 2.4 *Data analyses: effects of biomass prior to production on charcoal site patterns*

We extracted average aboveground biomass of the year 2017 for the charcoal sites of 2019. We first converted the charcoal site map into polygons so that each polygon covers a harvesting area of a charcoal site. We did this by drawing a polygon around each patch of raster cells classified as charcoal site with high robustness in QGIS, using the function "polygonize", which creates vector polygons for all pixels of a raster that are connected to each other and share a common pixel value (QGIS Development Team 2022). Second, we extracted aboveground biomass data within each of the polygons and calculated the mean aboveground biomass prior to charcoal production for each polygon. As the aboveground biomass data used in this study has a spatial resolution of 100 m and our charcoal site map a resolution of 30 m, the results of this spatial assessment did only not reflect average biomass availability prior to charcoal production within charcoal sites but also the average aboveground biomass availability prior to production in the area directly surrounding charcoal sites of the year 2019. Therefore, the mean aboveground biomass values we extracted within each charcoal site polygon may either reflect a slight over- or underestimation of the aboveground biomass in each of the charcoal sites. Third, we extracted patch metric values for each charcoal site and calculated correlations between mean aboveground biomass and patch metrics per village and for the entire dataset, using a Spearman rank ($\rho$) correlation (Zar 1972). This allowed us to compare OA-villages and CB-villages. We used the Spearman rank correlation because our data was not normally distributed upon examining histograms and outputs of the Shapiro-Wilk test and because normality could not be derived through data transformations. Fourth, we conducted a Principal Component Analysis (PCA) to visualize the variation in the complete dataset and to observe the directionality of correlations between aboveground biomass prior to charcoal production and patch metrics within a two-dimensional space. We scaled data to remove effects of different units of variables because this causes different levels of variations. Scaling was done using the generic "scale" function of the "base" R-package, which calculates the mean and standard deviation of each variable and uses these to scale each input per variable by subtracting the mean and dividing it by the standard deviation of the variable. To visualize the distribution of different villages within the PCA space, we color coded data points per village and drew ellipses over these data points, using an ellipse level of 0.5. Fifth, we repeated Spearman rank correlation and PCA analyses for charcoal sites larger than 1 ha to assess correlations between aboveground biomass availability and patch metrics in larger charcoal sites. This, because large charcoal sites were underrepresented in the data and the correlations within these sites may have been overshadowed by overrepresented small charcoal sites. Finally, we assessed differences in total aboveground biomass availability by summing the available aboveground biomass, irrespective of land cover type, to get an indication of disparities in access to forest biomass between study villages.

### 2.5 *Data analyses: effects of travel distance on charcoal site patterns and biomass*

To assess effects of travel distance on charcoal site patterns and biomass, we first identified village center locations by visually inspecting VHR satellite imagery in Google Earth. We defined the village center as the center of an area with the most extensive coverage of buildings within a village boundary. Because we conducted fieldwork in the study villages in 2019, we were aware of the location of the main village centers of our study sites and used this knowledge as reference to pinpoint the village center. Second, we used a radial segmentation approach (Bashar *et al* 2014) to recalculate the three landscape metrics within buffers of 200 m width that formed a moving window in donut shape. We then clipped the buffers to study village extent. The buffers moved their inner edge with a distance of 200 m per buffer, expanding in area but not in width. Hence, the buffers did not overlap each other but covered their own specific area in the village. We did not overlap buffers because recent research indicated that non-overlapping sliding widows and overlapping sliding windows, such as the donut-shaped buffers used in our study, achieve the same performance (Dehghani *et al* 2019). Third, we clipped the charcoal site map by each of the buffers, calculated the mean patch area, Euclidean nearest-neighbor distance and aboveground biomass prior to charcoal production within the charcoal site polygons per buffer, and plotted it against distance to the village center. The maximum distance from village center to the village boundary furthest away from this center was approximately 13 km. Finally, we conducted a Loess regression to assess trends in aboveground biomass prior to charcoal production and patch metrics with distance from the village center. A Loess regression is a non-parametric method that fits a smooth nonlinear curve through data points of a scatter plot based on a moving locally weighted regression (Cleveland and Loader 1996). We used the function "loess" of the R-package "stats", with the respective metrics as the dependent variables and distance to the village center as independent variable. We set the smoothing parameter (i.e., "span") at 0.5 to assess general data trends. We used the function "predict" of the R-package "stats" to predict Loess curves. We determined the R-squared ($r^2$) of the Loess regression, calculated as 1 minus the sum of the dependent variable divided by the sum of the residuals (Lewis-Beck and Skalaban 1990) to determine the proportion of variation in aboveground biomass prior to charcoal production and patch metrics that is explained by distance to the village center. To assess effects of buffer width, we conducted a sensitivity analysis, were we changed the buffer width to 100 m and 300 m. This provided us with an indication of the effect buffer width has on mean aboveground biomass and patch metric visualizations with distance from village centers.

Because buffer areas depend on the buffer location and village shape, we conducted an additional sensitivity analysis to assess whether charcoal producers choose their charcoal site locations randomly or whether social-ecological variables, such as travel distance from village centers and aboveground biomass availability, influence them. To do so, we compared the total number of charcoal sites observed per buffer with the number that would randomly be expected. First, we randomly distributed the same number of charcoal sites we identified through our remote sensing analysis within the boundary of each study village, using the function "spsample" of the R-package "sp" (González 2010), and set the type on "nonaligned", meaning that the sites were distributed throughout the village in an unorganized way. Second, we determined the total number of randomly distributed charcoal sites present in each consecutive buffer, summed this number and divided it by the village area each buffer covered to obtain relative numbers of randomly distributed charcoal sites per buffer. We divided the outcome by 1,000,000 to derive the number of charcoal sites per area in $km^{-2}$. We calculated each buffer area using the function "area" of the R-package "raster" (van Etten *et al* 2022) with buffers clipped to village extent in the form of a "SpatialPolygons" object as input. We repeated this process 200 times per village to calculate a 95% confidence interval that reflects the expected variation in the number of randomly distributed charcoal sites per buffer area. Third, we extracted the total number of charcoal sites that were detected through our remote sensing approach per buffer and divided it by the buffer areas per village. For this purpose we converted charcoal sites into points that reflect their respective polygon center, allowing us to plot the actually observed relative number of charcoal sites per buffer and the confidence interval for randomly expected relative number of charcoal sites per study village.

### *2.6 Data analyses: effects of governance on charcoal site patterns*

We compared patch metrics per village to understand effects of governance on the size, shape and density of charcoal sites. We used the non-parametric Kruskal-Wallis test to assess whether statistically significant differences exist in the mean of patch metrics of all villages (Breslow 1970). The Kruskal-Wallis test resembles a one-way ANOVA and provides a p-value that signals the significance of the difference between two groups (i.e., $p\text{-value} < 0.05$), in our case two study villages, as well as a Chi-square indicating the association between the groups. We also tested whether the distributions of patch metrics differed from each other, using the two-sample Kolmogorov-Smirnov tests (Klotz 1967), which provides a p-value that indicates a significant difference between distributions of two datasets (i.e., $p\text{-value} < 0.05$), as well as a D-statistic, which provides the magnitude of the difference between two distributions. We assessed whether patch metrics and mean aboveground biomass prior to charcoal production of charcoal sites within designated areas differed from those outside of designated areas in CB-villages, using the Kruskal-Wallis test, and tested differences in distributions using the Kolmogorov-Smirnov test. This allowed us to evaluate the adherence of charcoal producers to harvesting plan guidelines in CB-villages. We calculated mean aboveground biomass in charcoal sites prior to production because we expected that charcoal producers may be tempted to produce outside of designated areas if they find higher biomass levels in these areas.

We conducted all data analyses in R (Team 2019).

## 3. Results

### *3.1 Effects of biomass prior to production on charcoal site patterns*

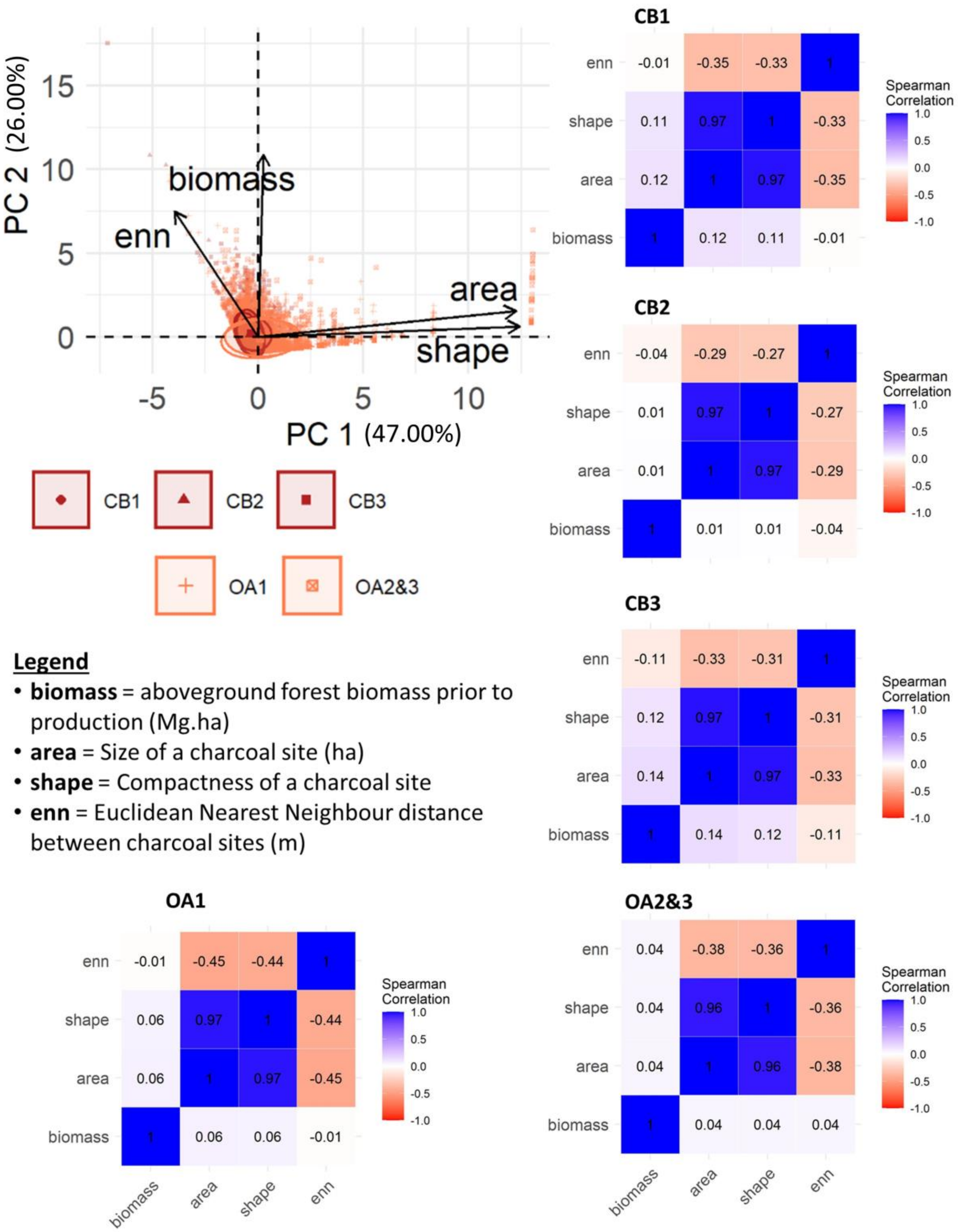
We find weak positive correlations between charcoal site area and mean aboveground biomass availability prior to charcoal production in all study villages (between $\rho$ = 0.01, p-value = 0.630 and $\rho$ = 0.14, p-value = 0.000***), with CB1 and CB3 showing highest correlations ($\rho$ = 0.12, p-value = 0.006** and $\rho$ = 0.14, p-value = 0.000***, respectively) (Fig. 3). We also find weak positive correlations between charcoal site shape and mean aboveground biomass availability prior to charcoal production in all study villages (between $\rho$ = 0.01, p-value = 0.742 and $\rho$ = 0.12, p-value = 0.002**), with CB1 and CB3 again showing highest correlations ($\rho$ = 0.11, p-value = 0.012* and $\rho$ = 0.12, p-value = 0.002**, respectively). Finally, we find weak negative correlations between Euclidean nearest-neighbor distance and mean aboveground biomass prior to charcoal production in all study villages except for OA2&3 (between $\rho$ = -0.01, p-value = 0.829 and $\rho$ = -0.11, p-value = 0.005**), with CB3 showing the highest correlation. In OA2&3, we observe a weak positive correlation between mean aboveground biomass prior to charcoal production and Euclidean nearest-neighbor distance ($\rho$ = 0.04, p-value = 0.012*). When assessing the variation in the different datasets in a two dimensional PCA space, we find a separation between Euclidean nearest-neighbor distance and patch area and shape along PC1, while aboveground biomass stands orthogonally to these variables along PC2 (Fig. 3). The first axis of the PCA explains the variance in size and shape of charcoal sites, while the second axis explains the Euclidean nearest-neighbor distance and mean aboveground biomass prior to charcoal production.

When only considering large patches (> 1 ha), we find higher correlations between aboveground biomass prior to charcoal production and patch metrics for CB-villages, in particular in CB1 (Appendix Fig. A2). In CB1, we find that aboveground biomass prior to charcoal production negatively correlates with patch area for large patches ($\rho$ = -0.26, p-value = 0.104). We also observe a positive significant correlation between aboveground biomass prior to charcoal production and patch shape ($\rho$ = -0.34, p-value = 0.031*) and a positive correlation with Euclidean nearest-neighbor distance ($\rho$ = 0.10, p-value = 0.540). In CB2, however, we find a positive but non-significant correlation between aboveground biomass prior to charcoal production and patch area ($\rho$ = 0.26, p-value = 0.056), while both patch shape ($\rho$ = -0.30, p-value = 0.027*) and Euclidean nearest-neighbor distance ($\rho$ = -0.2, p-value = 0.131) are negatively correlated with aboveground biomass prior to charcoal production. In CB3, we find positive correlations between aboveground biomass prior to charcoal production, patch area ($\rho$ = -0.14, p-value = 0.000***) and patch shape ($\rho$ = -0.12, p-value = 0.002**), while Euclidean nearest-neighbor distance negatively correlates ($\rho$ = -0.11, p-value = 0.005**). In OA2&3, we find similar correlation patterns between large patches and all patches together. In OA1, we observe a weak negative significant correlation between aboveground biomass prior to production and patch area ($\rho$ = -0.11, p-value = 0.044*), while Euclidean nearest-neighbor distance ($\rho$ = -0.11, p-value = 0.150**) and patch shape ($\rho$ = -0.11, p-value = 0.708) exhibit weak non-significant positive correlations with aboveground biomass. The overall pattern in the PCA does not change upon analyzing large patches (Appendix Fig. A2), but directions of variation along the two PCA axes are reversed for both PC1 and PC2.

Overall, OA-villages have a higher total amount of available aboveground biomass (OA1: 245,292 Mg, OA2&3: 627,101 Mg) than CB-villages (CB1: 68,469 Mg, CB2: 137,268 Mg, CB3: 129,550), in particular OA2&3 (this includes all aboveground biomass found in the villages, not specified for forest areas). OA-villages include patches with relatively higher aboveground biomass per hectare than CB-villages (Fig. 2). These patches are mainly located at higher elevation, and in the case of OA1, at relatively large distance from the village center (between 2 and 6 km). In CB1 and CB2 patches of relatively high aboveground biomass per hectare are spread throughout the village, while in CB3 relatively high aboveground biomass can be found at a distance of 3 km from the village center.

### *3.2 Effects of travel distance on charcoal site patterns and biomass*

We find a differentiation in the observed number of charcoal production sites per buffer and the number that would randomly be expected for all study villages. In both OA-villages we observe peaks in the number of charcoal sites and charcoal site size (Fig. 4 and 5). In OA1, we observe a peak in the number of charcoal sites between 6 km and 10 km distance from the village center, while we observe a peak in charcoal site area up to approximately 4 ha between 5 and 8 km. In OA2&3, we observe two peaks in the number of charcoal sites between 2 and 6 km and between 6 and 10 km from the village center. However, we only observe one large peak in charcoal site area up to approximately 4 ha between 4 and 7 km of the village center. In both OA-villages, we observe a gradual increase in mean aboveground biomass availability in charcoal sites with distance from the village center. Yet, we observe limited differences in Euclidean nearest-neighbor distance between charcoal sites with distance from the village center in OA-villages.



**Legend**

- **biomass** = aboveground forest biomass prior to production (Mg.ha)
- **area** = Size of a charcoal site (ha)
- **shape** = Compactness of a charcoal site
- **enn** = Euclidean Nearest Neighbour distance between charcoal sites (m)

**CB1**

| | biomass | area | shape | enn |
|---|---|---|---|---|
| enn | -0.01 | -0.35 | -0.33 | 1 |
| shape | 0.11 | 0.97 | 1 | -0.33 |
| area | 0.12 | 1 | 0.97 | -0.35 |
| biomass | 1 | 0.12 | 0.11 | -0.01 |

**CB2**

| | biomass | area | shape | enn |
|---|---|---|---|---|
| enn | -0.04 | -0.29 | -0.27 | 1 |
| shape | 0.01 | 0.97 | 1 | -0.27 |
| area | 0.01 | 1 | 0.97 | -0.29 |
| biomass | 1 | 0.01 | 0.01 | -0.04 |

**CB3**

| | biomass | area | shape | enn |
|---|---|---|---|---|
| enn | -0.11 | -0.33 | -0.31 | 1 |
| shape | 0.12 | 0.97 | 1 | -0.31 |
| area | 0.14 | 1 | 0.97 | -0.33 |
| biomass | 1 | 0.14 | 0.12 | -0.11 |

**OA1**

| | biomass | area | shape | enn |
|---|---|---|---|---|
| enn | -0.01 | -0.45 | -0.44 | 1 |
| shape | 0.06 | 0.97 | 1 | -0.44 |
| area | 0.06 | 1 | 0.97 | -0.45 |
| biomass | 1 | 0.06 | 0.06 | -0.01 |

**OA2&3**

| | biomass | area | shape | enn |
|---|---|---|---|---|
| enn | 0.04 | -0.38 | -0.36 | 1 |
| shape | 0.04 | 0.96 | 1 | -0.36 |
| area | 0.04 | 1 | 0.96 | -0.38 |
| biomass | 1 | 0.04 | 0.04 | 0.04 |

**Figure 3.** Principal component analysis (PCA) and Spearman correlation matrices showing correlations between patch metrics and mean aboveground biomass prior to charcoal production for all high robustness charcoal patches detected with our remote sensing approach. CB-villages are those villages under community-based natural resources management (CBNRM) and OA-villages are those under open access. We observe strong correlations between patch metrics and weak correlations between patch metrics and mean aboveground biomass prior to charcoal production. OA2 and OA3 are located within the same village boundary because OA3 had only just received the status of village at the time of study and no formal boundary of the village had been determined.

In CB-villages, we find varying trends in the number of charcoal sites, their patch area and Euclidean nearest-neighbor distance and mean aboveground biomass prior to charcoal production with distance from the village center (Fig. 4 and 5). In CB1, we observe two peaks in the number of charcoal sites per

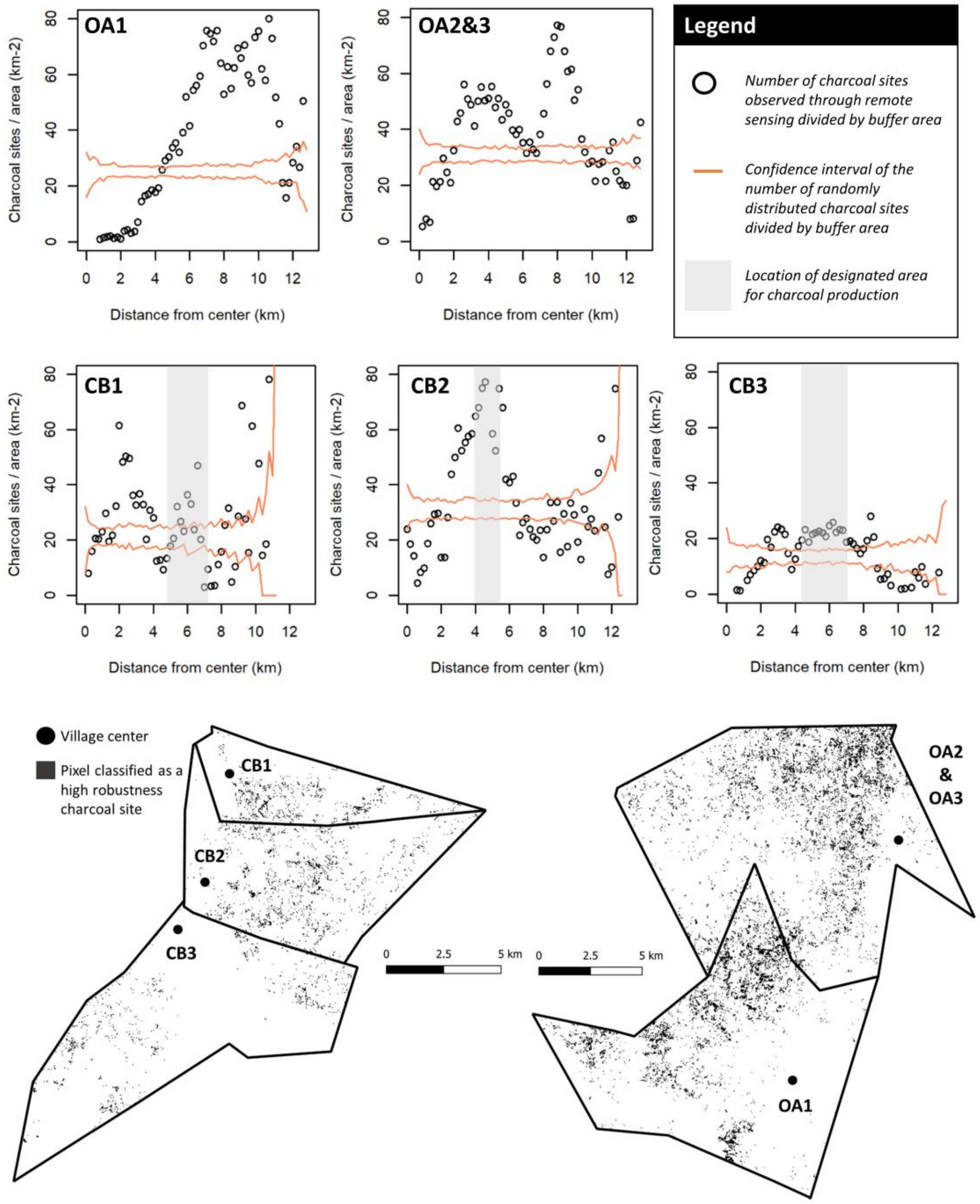


**Figure 4.** We visualize the number of charcoal sites detected through remote sensing within moving buffers divided by the area the buffer covered in km2 per study village (dots). This provides an indication of the relative distribution of charcoal sites across the study villages. Each 200 m buffer was cut to the extent of the study village boundaries. The confidence intervals indicate the number of charcoal sites divided by area of the buffer they occur in that would be expected if charcoal sites were distributed at random. We observe strong correlations between patch metrics and weak correlations between patch metrics and mean aboveground biomass prior to charcoal production. CB-villages are those villages under community-based natural resources management (CBNRM) and OA-villages are those under open access. OA2 and OA3 are located within the same village boundary because OA3 had only just received the status of village at the time of study and no formal boundary of the village had been determined.

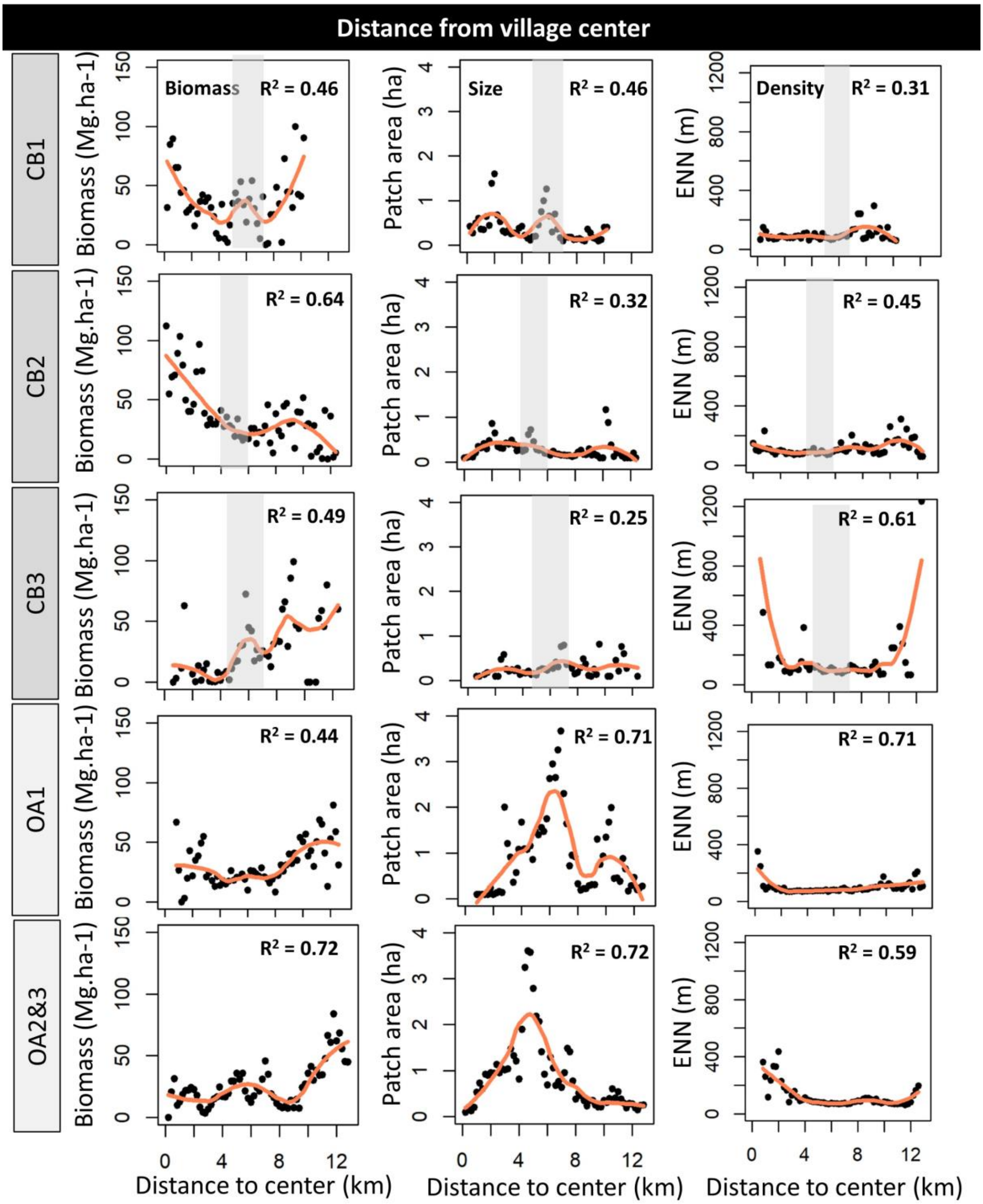


**Figure 5.** Mean aboveground biomass, patch area (i.e., patch size) and Euclidean nearest-neighbor distance (ENN) (i.e., density of patches) of charcoal sites in 200 m buffers that move from the village center outwards with steps of 200 m up to a distance of 13 km from the village center. OA = villages under open access and CB = villages under community-based natural resources management (CBNRM). OA2 and OA3 are located within the same village boundary because OA3 had only just received the status of village at the time of study and no formal boundary of the village had been determined. The gray areas in the CB-village plots indicate the distance from the village center at which the designated area for charcoal production is situated.

buffer area between 1.5 and 3.5 km and between 5 and 7 km; the latter coinciding with the location of the designated forest area for charcoal production. We also observe two small peaks in charcoal site size between 1 and 3 km and between 5 and 7 km. Yet, we observe limited variation in Euclidean nearest-neighbor distance and mean aboveground biomass levels prior to charcoal production follows a parabola shape with relatively high mean aboveground biomass close to the village center and between 9 and 11 km from the village center. The drop in mean aboveground biomass coincides with the designated area of CB1. In CB2, we observe one clear peak in the number of charcoal sites between 3 and 6 km from the village center, coinciding with the designated area. In CB2, we do not observe peaks in charcoal site area and Euclidean nearest-neighbor distance remains relatively constant. However, we do observe a linear decline in mean aboveground biomass prior to charcoal production with distance from the village center. In CB3, we observe a flattened peak in the number of charcoal sites between 2 and 8 km from the village center, roughly coinciding with the designated area. We observe limited variation in charcoal site size in CB3 but observe variations in Euclidean nearest-neighbor distance close to the village center and between 10 and 13 km from the village center. Mean aboveground biomass prior to charcoal production increases with distance from the village center in CB3, comparable to the increases observed in OA-villages.

A sensitivity analysis with different buffer widths does not change the overall spatial patterns observed with distance from the village center, indicating that our buffer analysis provides robust results (Appendix Fig A3).

### 3.3 *Effects of governance on charcoal site patterns*

We find differences between OA and CB-villages in the area covered by charcoal sites. We find that 2.46% of CB-villages, and 6.51% of OA-villages are covered with charcoal sites. Charcoal sites cover 0.99 km$^2$ in CB1 ($n_{\text{patches}} = 530$), 1.85 km$^2$ in CB2 ($n_{\text{patches}} = 1110$), 1.04 km$^2$ in CB3 ($n_{\text{patches}} = 689$), 6.84 km$^2$ in OA1 ($n_{\text{patches}} = 2068$), and 9.29 km$^2$ in OA2&3 ($n_{\text{patches}} = 3466$). Interesting, only a relatively small proportion of charcoal sites is found within designated areas for charcoal production in CB-villages (16.04% in CB1, 10.00% in CB2, and 9.72% in CB3). Overall, we observe that charcoal sites in OA-villages are significantly larger and more irregular in shape than those of CB-villages (Fig. 6, Appendix Table A1-A3). Besides this, OA-villages have a lower Euclidean nearest-neighbor distance than CB2 and CB3, although Euclidean nearest-neighbor distance in CB1 is lower compared to OA-villages. Overall, we observed larger standard deviations in patch area and patch shape in OA-villages than in CB-villages, as well as for Euclidean nearest-neighbor distance for CB2 and CB3. Besides this, we observe a significantly different distribution of charcoal site area and shape in OA-villages than in CB-villages (Appendix Table A4 and A5), as well as for Euclidean nearest-neighbor distance for CB2 and CB3 (Appendix Table A6) upon assessing results of the Kolmogorov-Smirnov test. We also observe more outliers for patch area in OA-villages compared to CB-villages.

Table 2 indicates limited differences between patch metrics and mean aboveground biomass prior to charcoal production between those charcoal sites inside and those outside of designated harvesting areas in CB-villages. Nevertheless, we find a significantly larger patch area inside the designated harvesting area of CB1 than outside this area. We also observe a significantly larger Euclidean nearest-neighbor distance outside than inside of designated areas in CB2 and CB3, and we find significant differences in its distribution in CB3. Finally, we observe a significantly lower mean aboveground biomass prior to charcoal production inside than outside of the designated area in CB3. The distribution of mean aboveground biomass prior to charcoal production outside of the designated area of CB2 differs significantly from that inside of the area.

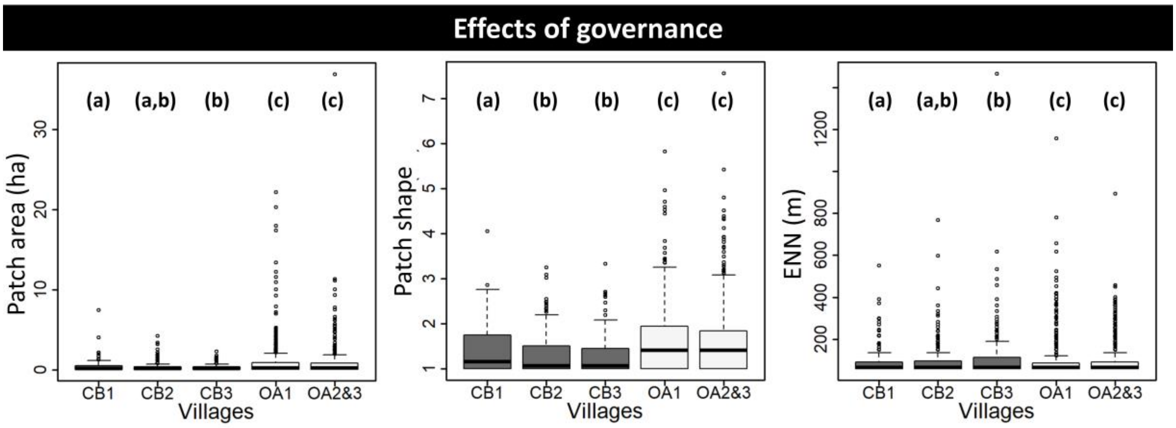
**Table 2.** Average differences in average aboveground biomass availability and patch metrics between charcoal sites within designated harvesting areas and outside of designated harvesting areas. area = patch area (ha), enn = Euclidean nearest-neighbor distance (m), shape = patch shape (see Table 1 for descriptions of patch metrics), and biomass = average aboveground biomass in harvesting areas of charcoal production sites prior to production (Mg.ha) (i.e., mean aboveground biomass calculated within the polygons covering the harvesting areas of charcoal sites). * = significant difference at p-value=0.05, ** = significant difference at p-value=0.01; *** = significant difference at p-value<0.001. CB stands for village under community-based natural resources management (CBNRM) for charcoal production (see Fig. 2 for study village overview).

| Indicator | | Inside of designated area | | Outside of designated area | | Kruskal-Wallis test | Kolmogorov-Smirnov test |
|---|---|---|---|---|---|---|---|
| | | *Mean* | *SD* | *Mean* | *SD* | *P-value and Chi-square* | *P-value and D-statistic* |
| **CB1** | *area* | 0.497 | 0.787 | 0.456 | 1.067 | $X^2_{(1, N=544)} = 3.9237$,<br>P-value = 0.0476* | D-statistic = 0.1458,<br>P-value = 0.0955 |
| | *shape* | 1.434 | 0.466 | 1.383 | 0.578 | $X^2_{(1, N=544)} = 3.5120$,<br>P-value = 0.0609 | D-statistic = 0.1437,<br>P-value = 0.1045 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | *enn* | 84.826 | 38.926 | 87.345 | 52.325 | $X^2_{(1, N = 544)}$ = 0.0034,<br>P-value = 0.9537 | D-statistic = 0.0713,<br>P-value = 0.8598 |
| | *Biomass* | 32.612 | 32.676 | 37.065 | 36.845 | $X^2_{(1, N = 544)}$ = 1.3946,<br>P-value = 0.2376 | D-statistic = 0.0950,<br>P-value = 0.5369 |
| CB2 | *area* | 0.254 | 0.261 | 0.328 | 0.550 | $X^2_{(1, N = 1124)}$ = 0.0896,<br>P-value = 0.7646 | D-statistic = 0.0530,<br>P-value = 0.9416 |
| | *shape* | 1.243 | 0.337 | 1.292 | 0.457 | $X^2_{(1, N = 1124)}$ = 1.0181,<br>P-value = 0.8931 | D-statistic = 0.0577,<br>P-value = 0.8938 |
| | *enn* | 80.790 | 28.461 | 96.931 | 86.067 | $X^2_{(1, N = 1124)}$ = 5.1491,<br>P-value = 0.0233* | D-statistic = 0.1179,<br>P-value = 0.1241 |
| | *Biomass* | 24.135 | 24.785 | 37.388 | 44.982 | $X^2_{(1, N = 1124)}$ = 1.4204,<br>P-value = 0.2333 | D-statistic = 0.1714,<br>P-value = 0.0056* |
| CB3 | *area* | 0.206 | 0.189 | 0.298 | 0.417 | $X^2_{(1, N = 704)}$ = 2.0419,<br>P-value = 0.1530 | D-statistic = 0.1096,<br>P-value = 0.4615 |
| | *shape* | 1.238 | 0.428 | 1.287 | 0.478 | $X^2_{(1, N = 704)}$ = 1.6741,<br>P-value = 0.1957 | D-statistic = 0.1064,<br>P-value = 0.4997 |
| | *enn* | 11.266 | 50.681 | 107.945 | 102.216 | $X^2_{(1, N = 704)}$ = 9.8283,<br>P-value = 0.0017** | D-statistic = 0.2494,<br>P-value = 0.0011** |
| | *Biomass* | 14.537 | 23.484 | 27.526 | 39.520 | $X^2_{(1, N = 704)}$ = 7.5288,<br>P-value = 0.0061* | D-statistic = 0.1653,<br>P-value = 0.0728 |

## 4. Discussion

We examined impacts of social-ecological drivers on charcoal site patterns at a landscape scale. We find limited direct effects of mean aboveground biomass on charcoal site size, shape and density, independent of the governance system in place. However, we do find effects of travel distance from the village center outwards on the number and size of charcoal sites in OA-villages, with a peak intermediate distance from the village center, likely because charcoal producers consider the tradeoff between the distance they need to travel to produce charcoal and the amount of aboveground biomass



| | Patch area (ha) | | Patch shape | | ENN (m) | |
|---|---|---|---|---|---|---|
| *Villages* | *Mean* | *ST dev* | *Mean* | *ST dev* | *Mean* | *ST dev* |
| ***CB1*** | 0.5616 | 1.2238 | 1.4477 | 0.6229 | 88.6622 | 55.3317 |
| ***CB2*** | 0.3878 | 0.6015 | 1.3395 | 0.4817 | 92.5665 | 59.4545 |
| ***CB3*** | 0.3475 | 0.4475 | 1.3445 | 0.5086 | 103.9444 | 95.0984 |
| ***OA1*** | 1.4030 | 3.4179 | 1.6611 | 0.9284 | 84.9996 | 61.4581 |
| ***OA2&3*** | 1.2060 | 3.8891 | 1.6449 | 0.9819 | 82.7816 | 46.8992 |

**Figure 6.** Statistical differences between villages have been computed for the effect of governance, using the non-parametric Kruskal-Wallis test (Appendix Table A1-A3). Statistical differences between the distributions of each study village have been determined using the Kolmogorov-Smirnov test (Appendix Table A4-A6). Statistical differences between study villages have been indicate with letters in the boxplots, where similar letters indicate no significant difference and different levels indicate a significant difference. OA = villages under open access and CB = villages under community-based natural resources management (CBNRM). OA2 and OA3 are located within the same village boundary, as OA3 had only just received the status of village at the time of this study and no formal boundary of the village had been determined. Mean = the mean of a patch index per study village. ST dev = the standard deviation of a patch index per study village.

available. This is in line with our hypothesis that charcoal producers prefer to produce close to the village center but move further away upon a depletion of forest biomass. Overall, we find that governance has a strong effect on charcoal site patterns at a landscape scale, as significant differentiations occur between OA and CB-villages in charcoal site size, shape and density, and because we find limited differentiations in charcoal site patterns with distance to the village center and biomass availability. These results indicate that harvesting plans mainly drive charcoal site patterns in CB-villages, as opposed to ecological and geographical processes. Nevertheless, abundant production of charcoal observed outside designated areas indicates a mismatch between governance goals in reality under CBNRM.

### *4.1 Effects of biomass prior to charcoal production*

In contrast with our hypothesis, we find weak correlations between mean aboveground biomass availability prior to charcoal production and patch metrics, which suggests limited effects of aboveground biomass availability as a driver of charcoal site area, shape and density. However, we find stronger correlations between aboveground biomass availability and patch metrics in larger patches of CB-villages. The negative correlations between mean aboveground biomass availability prior to production and patch area, as well as shape of charcoal sites larger than 1 ha in CB1 could indicate that charcoal producers harvest larger forest areas upon low biomass availability, potentially to gather enough biomass to build a kiln. In contrast, positive correlations between aboveground biomass availability prior to charcoal production and patch area in patches larger than 1 ha in CB2 and CB3 may suggest that charcoal producers are tempted to harvest larger forest areas upon high mean aboveground biomass availability, potentially because this provides them with more charcoal and, hence, more income from charcoal sales. These results reveal a variable response of charcoal producers to mean aboveground biomass availability.

Limited correlations between mean aboveground biomass and patch metrics suggest that other environmental factors may affect charcoal site patterns, such as elevation, tree size and tree species composition, as well as competing land uses. First, charcoal production is difficult in mountainous areas, such as the hills in OA-villages because steep slopes challenge the construction of a kiln and tree harvesting (Ko *et al* 2011). We observe such elevation impacts in OA2&3 because charcoal site numbers drop at 6 km and after 10 km from the village center, which coincides with mountain ranges (Fig. 4). Second, trees used for charcoal production may be heavy, difficult to move and/or to pile on top of each other to form a kiln (Ihalainen *et al* 2020), challenging the movement of heavy logs over long distances. This may restrict harvesting area size because charcoal producers may avoid to cut trees far from their kiln. Third, charcoal producers prefer to harvest large hardwood trees first (Ndegwa *et al* 2018) because they produce charcoal of high calorific value that does not break easily (Malimbwi and Zahabu 2008). These trees have high wood density (Ragland *et al* 1991) and, hence, are relatively heavy and difficult to move. Therefore, the distribution of trees that provide high quality charcoal may influence the size, shape and distribution of the harvesting areas subjected to selective cutting. For example, charcoal producers who engage in selective cutting practices may produce smaller harvesting areas upon high density of suitable trees, and larger harvesting areas at low density. Active selection of places with abundant suitable tree species may also explain why charcoal production usually occurs in small patches across the landscape, rather than through continuous expansion of one charcoal site. Fourth, collaboration between charcoal producers may change charcoal site patterns, as this allows producers to cut heavier trees and build larger kilns together. Building large kilns likely enhances the efficiency of charcoal production as only one kiln needs to be guarded and heavy hardwood species that provide high quality charcoal can be used. Finally, land uses that intertwine forest areas, such as agriculture and built-up areas, may restrict the size, shape and especially the density and distribution of charcoal sites.

### *4.2 Effects of distance from village center*

We observe an increase in mean aboveground biomass availability prior to charcoal production and large peaks in the number of charcoal sites and the mean area each site covers with distance from the village center in OA-villages. These results support our hypotheses that charcoal production first occurs close to villages until aboveground forest biomass resources are depleted, after which producers move further away from the village center (Ko *et al* 2011, Sedano *et al* 2016). The pattern coincides with the characteristic "pre-boom", "boom" and "post-boom" zones observed in previous studies (Baumert *et al* 2016). The large peaks in charcoal site area and the number of charcoal sites in OA-villages with distance from the village center show the preferred zone for charcoal production, corresponding to a boom area (Baumert *et al* 2016). In contrast, areas close to the village center show relatively low mean aboveground biomass, charcoal site numbers and patch area, indicating that charcoal producers may have shifted from this so-called post-boom area, to the boom area due to biomass depletion (Baumert *et al* 2016). Finally, areas far from the village center show relatively small charcoal sites and low charcoal site numbers, yet high forest aboveground biomass availability, suggesting a pre-boom area, which has not yet been subjected to intensive charcoal production (Baumert *et al* 2016). Forest resources may diminish over time in boom areas, depending on forest regeneration rates, charcoal production rates and elevation. This may motivate charcoal producers to more heavily exploit pre-boom areas in the future. However, similar values in Euclidean nearest-neighbor irrespective of distance from the village center, indicate that charcoal continues to be produced at similar proximity to other charcoal sites in boom areas as in pre- and post-boom areas, suggesting that producers do not yet face severe aboveground biomass shortages and overall aboveground biomass availability in OA-villages is generally higher. Overall the pattern observed in OA-villages matches general patterns of deforestation and forest degradation observed for other drivers (e.g., timber production) (Laurance *et al* 2009, Mcgarigal *et al* 2001). Interestingly, we do not observe these clear pre-boom, boom, post-boom dynamics in CB-villages, indicating an effect of governance on production patterns.

### *4.3 Effects of governance*

In line with our hypothesis, we show that charcoal sites in OA-villages are generally larger, more irregular in shape, and less densely distributed than those of CB-villages, likely due to adherence to the harvesting guidelines specified in the harvesting plan on the sizes and shapes of harvesting areas (Ishengoma *et al* 2016). We also show a relatively constant charcoal site size across CB-villages compared to OA-villages, and a lower relative extent of charcoal sites. These results suggest that governance has the power to shape charcoal site patterns in the landscape. The similarity between charcoal site characteristics in CB-villages may have been promoted by training schemes and formalized institutions that promote collaboration and interactions between charcoal producers (e.g., charcoal producers associations) (van 't Veen *et al* in review). This intensive collaboration may have enhanced knowledge sharing between charcoal producers about production practices, resulting in similar production manners. Overall, our observation that governance influences charcoal site patterns are in line with studies that find improved forest management (Fajar and Kim 2019), as well as reductions in deforestation (Nath *et al* 2016), forest degradation (Fajar and Kim 2019), and biodiversity loss under CBNRM (Deschamps 2000), with the potential to enrich livelihoods (Mukul *et al* 2012).

Despite signs of adherence to specific aspects of the CBNRM harvesting plan in CB-villages, we observe that charcoal is produced throughout the entire village, not only in areas designated for charcoal production (Table 2, Fig. 4). This indicates that charcoal producers do not fully adhere to the harvesting plan in place. Additionally, although governance transitions to CBNRM appear to disrupt waves of charcoal production spreading from the village center, it does not have a uniform effect across CB-villages. This finding is in line with studies that report mismatches between governance goals of CBNRM and reality (Rasolofoson *et al* 2015). Effective CBNRM requires efforts on social (e.g., collaboration in forest management) and ecological aspects (e.g., enhancement of forest productivity) (Mazur and Stakhanov 2008). Social processes that could explain charcoal production outside of designated areas in CB-villages are challenges in CBNRM (Purnomo *et al* 2020), including power relations that jeopardize CBNRM goals (Niedzialkowski *et al* 2012), a low sustained government support to local communities, and limited awareness of rules and regulations implemented under CBNRM (Cagalanan 2015). For example, limited interactions between charcoal producers and members of District and National governance agencies (van 't Veen *et al* in review) may result in limited awareness of the (importance of) designated areas for forest conservation.

An ecological process that could explain charcoal production outside of designated areas in CB-villages may be an overall lower aboveground forest biomass availability compared to OA-villages (Fig. 5).

Miombo woodland dynamics are affected by both geography (e.g., mountain ranges) and ecology, with higher forest biomass levels observed in wet miombo woodlands (73 t.ha$^{-1}$) than in dry miombo woodlands (56 t.ha$^{-1}$) (Chidumayo 2019). In our study area, OA-villages are mountainous, while CB-villages are relatively flat. Wet miombo woodlands are more common in mountainous areas because of lower temperatures at higher elevation than low elevation (Jinga and Palagi 2020). Therefore, it is likely that the miombo woodlands of OA-villages receive relatively more rain than those in CB-villages and, hence, have a relatively higher forest carrying capacity. Ecological differences in overall biomass availability, forest carrying capacity and growth rates between OA-villages and CB-villages may create inequalities in aboveground biomass access and may challenge the sustainability of charcoal production (Chidumayo 2019). On the long term, this may lead to inequality in forest ecosystem service provisioning, in particular after multiple waves of charcoal production (Silva *et al* 2019). Besides this, tree species selection, as dictated by the CBNRM harvesting plan, may cause charcoal producers to harvest trees outside the designated areas because they are not allowed to harvest timber trees and trees with a diameter-at-breast-height smaller than 15 cm. For example, in CB3 on average less forest biomass is available inside designated harvesting areas than outside of these areas, potentially indicating an exhaustion of suitable aboveground biomass. Overall, our results emphasize the importance of monitoring the compliance of charcoal producers to CBNRM harvesting regulations to avoid unsustainable practices (van ’t Veen *et al* 2021), as well as to develop adaptable harvesting plans that consider limitations of aboveground biomass availability in designated areas and the effect this may have on producer behavior.

### *4.4 Lessons learned*

We based this research on a previous study during which we developed a remote sensing approach to identify charcoal sites. Although we tried to minimize uncertainty and error, mismatches occurred between the actual extent of charcoal sites and the extent predicted by our method (see Chapter 4 of this thesis). These mismatches may have influenced our results. Several considerations need to be considered concerning issues of scale in our study. First, the 100 m spatial resolution aboveground biomass map exceeds the size of small charcoal sites (i.e., one or two pixel sites). Therefore, we included the aboveground biomass in the surrounding area of small charcoal sites when assessing correlations between patch metrics and aboveground biomass. This may potentially explain the weak relationships between forest biomass and the spatial patterns of charcoal site because the majority of charcoal sites covered only one or two pixels. Second, we assumed that charcoal producers operate within the boundaries of their village extent, while they may travel outside of their village boundaries to produce charcoal. Third, OA2&3 consists of two villages, of which one only recently received formal recognition. In this analysis, we consider it one village, which raises questions about the effect of village boundaries on the results of our study. Fourth, charcoal production and aboveground biomass could have been influenced by roads or the exact locations of charcoal producer residencies (which might have been outside the village center), rather than distance to the village center. Finally, although the radial segmentation approach adopted in this study is useful to assess spatial dynamics and is well founded in landscape ecology studies (see (Bosch *et al* 2020), (Koper *et al* 2009), (Senf *et al* 2017)), the radius of the buffers is somewhat artificial. Nevertheless, we believe that distance from the village center is best measured in concentric circles around the village center because this best reflects actual travel distances of charcoal producers into the wider village area. Our sensitivity analysis also shows that buffer size and overlap do not affect the overall charcoal site area and density with distance from the village center (Appendix Fig. A3), highlighting the robustness of our approach.

## 5. Conclusion

Globally, charcoal production causes deforestation and forest degradation, which has the potential to alter forest dynamics, such as forest regeneration and biodiversity. Variability in charcoal site spatial characteristics (i.e., harvesting area size, shape, density and distribution) challenges the assessment of its spatiotemporal ecological and landscape implications. Here, we use remotely-sensed charcoal sites to examine effects of three potential drivers of charcoal production characteristics, (i) biomass availability prior to charcoal production, (ii) travel distance, and (iii) governance regime (open access and CBNRM). In contrast to our hypothesis, we do not find direct effects of forest biomass availability on charcoal production patterns in OA-villages. Rather we find a combined effect of travel distance to the village center and biomass availability on the distribution, number and size of charcoal sites.

Significant differences in the size, shape and density between OA-villages and CB-villages and a lack of corresponding peaks in charcoal site numbers, sizes and aboveground biomass availability prior to production in CB-villages suggest that governance has the power to alter charcoal production patterns in the landscape. Yet, production outside of designated areas reveals a mismatch between governance goals and reality in CB-villages. Hence, our study highlights both opportunities and challenges of CBNRM of charcoal production, which is relevant as transitions to CBNRM are being promoted to foster sustainable biomass-based renewable energy production. Overall, our study provides a first step into the development of social-ecological modelling approaches to spatially monitor and predict charcoal production patterns at a landscape scale and their impact on forest resources and biodiversity in the future.

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## Author contributions

The author contributions are based on CRediT (Contributor Roles Taxonomy), which aims to recognize individual author contributions, to facilitate collaborations and to diminish disputes among authors (https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement).

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# Chapter 6

## Effects of governance transitions on charcoal producer social networks

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**Chapter 4** and **Chapter 5** highlight the impact of charcoal production on resource units (i.e., forest use/natural capital) of charcoal production systems. Although these Chapters provide some spatiotemporal insight into the forest harvesting behavior of charcoal producers (i.e., the users), their impact on livelihoods remains unclear. There is a particular need to assess the access charcoal producers have to social networks, as these networks can shape governance and forest management through enhanced trust, knowledge exchange and reciprocity (Bodin and Crona 2009). Based on a systematic review of charcoal production systems I conducted, I can conclude that no scientific articles prior to August 2020 explicitly examined social networks of charcoal producers.

In **Chapter 6**, I partly close the knowledge gap on charcoal producer social networks. A comparison of social networks of charcoal producers in two charcoal production systems with different access characteristics informs me about the impact of a system transition on the social networks of charcoal producers. This Chapter paves the way for **Chapter 6** of this thesis, in which I explore the livelihood capitals of charcoal producers and their interactions.

**Figure 6.1** provides an overview of the social-ecological system components assessed in **Chapter 6**, their interactions, and the specific charcoal production systems compared. The **Supplementary Materials** of **Chapter 6** can be found in the **Appendix of Chapter 6** of

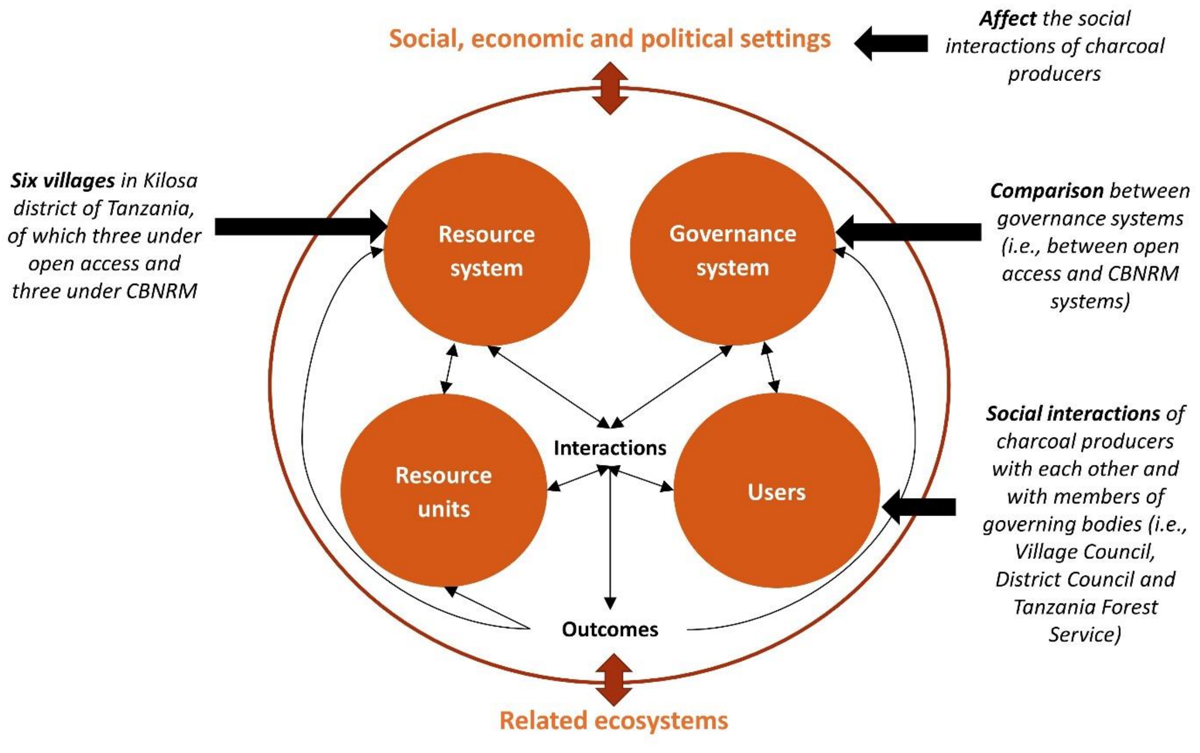

**Figure 6.1.** The social-ecological system components assessed in **Chapter 6**, their interactions, and the specific charcoal production systems compared. CBNRM = community-based natural resources management.

Submitted scientific paper

# Effects of governance transitions on charcoal producer social networks

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## Abstract

Charcoal production supports livelihood diversification but simultaneously results in up to 7% of deforestation worldwide and forest degradation. Governance transitions from open access to community-based natural resource management (CBNRM) aim to empower communities through rights and tenure provisioning to derive equitable distribution of charcoal benefits and sustainable forest use. CBNRM relies on the assumption that participatory forestry results in dense decentralized social networks that provide adaptive capacity to communities. Therefore, social networks under CBNRM should have strong connections between (i.e., bonding) and across governance levels (i.e., linking); yet limited studies provide robust evidence for this. We examine this hypothesis for charcoal producer networks in Kilosa District, Tanzania, where we conducted 160 interviews in three CBNRM and three open access villages. Our results show significantly stronger bonding in CBNRM than in open access villages but limited differences in linking. Additionally, CBNRM networks are denser and more decentralized with multiple nested communities compared to open access networks. We find that strong bonding likely relates to interaction formality, as CBNRM villages were supported to develop associations, trainings and participatory forestry schemes for charcoal producers, which enhances bonding through sporadic interactions. Limited linking reveals stronger interactions between producers themselves than with other governance levels, which could hinder forest governance. Our results suggest that (continued) efforts to formally enhance interactions between producers can assure strong bonding. However, signs of decay in formal institutions could compromise established interactions under CBNRM, and reveals challenges in its long-term continuation, which may be tackled through schemes that enhance linking.

**Keywords** Charcoal · social networks · social-ecological systems · transitions · community-based natural resources management (CBNRM) · cooperatives

## 1. Introduction

Production of biomass-based renewable energy does not only reduce carbon emissions globally by approximately 0.02–0.09% (Destek *et al* 2021), but also influences livelihoods involved in its value chains (Heck *et al* 2018). Charcoal is an important biomass-based renewable energy, which diversifies livelihoods and globally grants income to 40 million and energy to hundreds of millions of people (FAO 2017, Agyei *et al* 2018a, Baumert *et al* 2016). Currently, charcoal production mainly occurs in open access, defined as charcoal production systems where producers limitedly adhere to laws, rules and regulations (FAO 2017, Schure *et al* 2013, van 't Veen *et al* 2021). Under these conditions, charcoal production is linked to up to 7% of global deforestation and to forest degradation (Chidumayo and Gumbo 2013), including as by-product of agricultural expansion (Iiyama *et al* 2017). This causes declines of biodiversity and other forest-related ecosystem services (Zorrilla-Miras *et al* 2018, Woollen *et al* 2016). Numbers of people relying on charcoal to fulfill their livelihoods are expected to grow, leading to a 5% increase in demand by 2100 (Santos *et al* 2017, IEA 2014, Hillring 2006), potentially affecting forest resources further (Ahrends *et al* 2010, Woollen *et al* 2016, Vollmer *et al* 2017). A decline in available forest resources makes charcoal production more time consuming for producers (Baumert *et al* 2016, Schure *et al* 2014), causing a loss of income and livelihoods (Baumert *et al* 2016, Schure *et al* 2014). Hence, transitions in charcoal production systems to assure sustainable forest use and livelihoods are vital (FAO 2017, van 't Veen *et al* 2021).

Theory suggests that a transition to community-based natural resources management (CBNRM) could enable effective governance of common pool resources (Measham and Lumbasi 2013, Lyons 2013), such as forest resources shared among many (Ojha 2014, Schafer and Bell 2002) because it is based on good governance principles (Cox *et al* 2010, Gruber 2010, Measham and Lumbasi 2013). CBNRM aims to balance conservation and exploitation of shared natural resources by pursuing both environmental and socio-economic goals (e.g., equitable distribution of wealth and resources) (Armitage 2015). Successful CBNRM confides in public participation, interactions, and empowerment of stakeholders (Campbell & Vainio-Mattila, 2003; Scheberle, 2000), which enhances trust, increases knowledge and improves decision-making and sustainable resource use (Gruber 2010, Rotha 2009). Several studies suggest that formal communication systems, such as steering committees, cooperatives, and associations (Fabricius and Collins 2007, Maas *et al* 2014), may actively promote knowledge sharing among people (Allan and Curtis 2005, Olsson *et al* 2004). Hereby, it is important that responsibilities are shared and representatives from diverse social-economic classes are included (Campbell & Shackleton, 2001; Schnegg, 2018). This shared governance is expected to foster adaptive leadership, monitoring and accountability (Rihoy and Maguranyanga 2007), allowing for conflict resolution (Warner and Jones 1998), and enhancing adaptive capacity of communities that use this governance mode (Armitage 2015). As a result, successful governance under CBNRM is expected to result in or could be achieved through dense social networks (Friedman *et al* 2020, Schnegg 2018). However, often mismatches occur between governance goals and reality under CBNRM (Leach *et al* 1999), e.g., resulting from discontentment about livelihood benefits and corruption (Delgado-Serrano *et al* 2018). Hence, there is a need for systematic impact assessments of CBNRM, in particular on aspects that influence their success, such as social networks, to assess the extent to which governance objectives are realized.

Social network characteristics, including (i) network decentralization and heterogeneity, (ii) bonding and bridging, and (iii) linking, are important catalysts of sustainability transitions (Baird and Gray 2014, Beilin *et al* 2013, Bodin and Crona 2009). First, network decentralization, i.e., multiple central figures and sub-communities in networks, has been shown to enhance innovation and to buffer losses of relationships, which ultimately increases community resilience (Bodin and Crona 2009). Network heterogeneity, i.e., diversity of users along sub-communities, also enables community resilience by providing a portfolio of options through which governance goals can be achieved (Poortinga 2012, Lee 2020). Second, interactions between stakeholders with comparable roles in communities, i.e., bonding and bridging, enhances social cohesion (Cullen and Whiteford 2001, Musavengane and Kloppers 2020) because equality, quality and formality of interactions between people with comparable roles builds trust, reciprocity, and enables development of shared norms and values (Bhandari and Yasunobu 2009, Nenadovic and Epstein 2016, Nooteboom 2007). Third, connections between people operating at different hierarchical levels within a governance system, i.e., linking, may positively influence access to resources through regulatory power (Claridge 2018, İzmen and Üçdoğruk 2020, Marín *et al* 2012). Therefore, linking may result in equality of opportunity, because interactions across governance levels provides individuals and communities access to power, the ability to voice their concerns, the capacity to exchange information beyond a specific community (Aldrich 2011, Marín *et al* 2012, Tavits 2006), and it exposes communities to new ideas and values (Woolcock 2001), leading to long-term efficiency of governance (Grafton 2005, Hawkins and Maurer 2010, Musavengane and Kloppers 2020). Nevertheless, high bonding, bridging and linking may also foster corruption and nepotism (Claridge 2018), consolidation of social networks (Szreter and Woolcock 2004, Cofré-Bravo *et al* 2019), and the emergence of undesirable norms and values (Patulny and Svendsen 2007), with potentially negative outcomes for natural resources. Overall, poor users of natural resources often have fewer opportunities (Adhikari *et al* 2014, Behera and Engel 2006, Vyamana 2009) and higher opportunity costs (e.g., time restrictions), to enter and participate in CBNRM decision making (Luswaga and Nuppenau 2020, Vyamana 2009), which may reduce their social interactions and the influence they have over others (Fernández-Giménez *et al* 2015).

Here, we aim to understand whether governance transitions alter social network structure, focusing particularly on bonding and linking characteristics of social networks. More specifically, we examine whether interactions between charcoal producers themselves and with members of other governance levels differ between open access and CBNRM communities through counterfactual analysis (Fig. 1). We also assess whether equality (i.e., social-economic wealth status), quality (i.e., frequency of interactions, satisfaction with the interaction) and formality of relationships (i.e., membership of an association, who charcoal producers interact with) relate to charcoal producers' social network characteristics. In open access systems, we expect either limited interactions because of illegal charcoal production or numerous interactions between charcoal producers to support to each other. Because of this, we also expect few interactions between charcoal producers and members of governance agencies in open access, overall producing relatively scattered networks and disconnected charcoal producer communities. In CBNRM systems, we expect numerous interactions between charcoal producers themselves and with governance agencies, because of the formalization of charcoal production, resulting in denser charcoal producer networks, with more bonding and linking and a higher quality of interactions. We expect that the opportunities to interact with others increase with socio-economic wealth status.

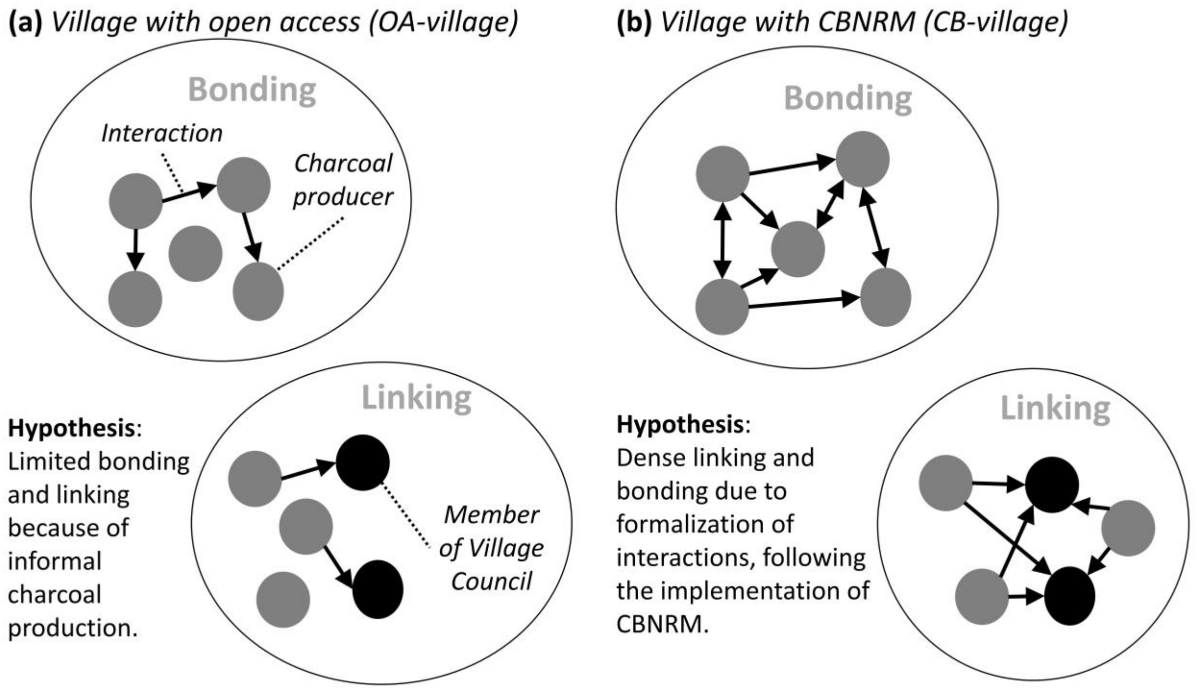

**Figure 1.** Hypothesized differences in bonding and linking in the social networks of charcoal producers under open access and community-based natural resources management (CBNRM). Bonding is defined as the interactions between people with comparable roles in the community, in this case interactions between charcoal producers. Linking is defined as interactions between people of different hierarchical levels, in this case interactions between charcoal producers and members of their Village Council (i.e., village government).

## 2. Material and Methods

To answer the research question, we conduct a counterfactual analysis (i.e., analysis during which outcomes of policy interventions are compared to a business as usual scenario) on survey data collected in 6 villages of which three under open access (i.e., business as usual) and three under CBNRM. We use the term CBNRM, rather then forest-related derivatives, such as community-based forest management (CBFM), and participatory forest management (PFM) because social networks are important under all forms of CBNRM, indicating the need to put our results in wider context.

### 2.1 Study area

We conducted this study in Kilosa District of Tanzania, located approximately 300 km west of Dar es Salaam. About 92% of Tanzania's population is dependent on wood fuel, mainly consumed as charcoal in urban areas, which causes 33.16% of deforestation (Ministry of Natural Resources & Tourism, 2015) and uncertain estimates of forest degradation. Multiple government agencies are involved in forest management in Tanzania, including Tanzania Forest Service (TFS) at national level, District governments and Wards at regional level, and Village Councils at local level (Lund, 2007; Mabele, 2020; Mustalahti & Lund, 2010). Village Councils may issue permits for harvesting trees to produce commercial timber, charcoal and other forest products within a designated forest area, called a Village Land Forest Reserve (VLFR) (Lund, 2007; Mabele, 2020; Mustalahti & Lund, 2010). To exercise this right, a Village Council must first develop a sustainable forest management plan, subjected to approval by the District Harvesting Committee (Lund, 2007; Mabele, 2020; Mustalahti & Lund, 2010). Once the Village Council has fulfilled legal requirements, it may allow harvesting of specified forest extents by individual or groups of charcoal producers (Lund, 2007; Mabele, 2020; Mustalahti & Lund, 2010).

We studied six villages, three involved in the Transforming Tanzania's Charcoal Sector (TTCS) project of Tanzania Forest Conservation Group (TFCG) (from here on referred to as CB-villages) and three villages that were not involved in this project (from here on referred to as OA-villages). To protect interviewees, the villages remain anonymous in this paper. The TTCS project aims to transform charcoal production to conserve forests and support livelihoods through CBNRM (Ishengoma *et al* 2016). The TTCS project was introduced in the year 2014 in the three CB-villages following official approval of their VLFR (Ishengoma *et al* 2016), which formalized charcoal production in compliance with a VLFR management plan (Ishengoma *et al* 2016, Doggart 2016). TFCG established and facilitated charcoal producer associations in CB-villages to organize charcoal production and assure representation and transmission of producers' viewpoints (Ishengoma *et al* 2016). In the studied CB-villages, only producers who are member of a charcoal producer association are allowed to produce charcoal. At the start of the TTCS project all charcoal producers received training on sustainable charcoal production and forest management (Ishengoma *et al* 2016).

The three OA-villages selected for this study were not part of the TTCS project. These villages do not have a VLFR. Therefore, charcoal production mainly occurs illegally under limited adherence to existing laws, rules and regulations (i.e., in open access). OA-villages provide a business as usual scenario to which we compare CB-villages. Although the management of charcoal production differs between the two village types, charcoal is derived in similar traditional fashion from forest resources, providing income and livelihood diversification benefits to charcoal producers. CB-villages are located adjacent to each other approximately 20 km South of Kilosa city, while OA-villages are located adjacent to each other approximately 30 km North of Kilosa city. Although some sporadic communication occurs between Village Council members of the two village types during assemblies, we expect that the large distance between the villages will largely prevent these interactions from influencing forest governance. TFCG and the District Council confirmed that no other forest-related third party projects were implemented in our study villages. Hence, we regard CB-villages and OA-villages as independent samples, which can be statistically compared through counterfactual analysis.

### 2.2 Data collection

We conducted 160 interviews with charcoal producers in July and August of 2020 across the six study villages. We used a stratified random sampling approach to select interviewees based on wealth status to ensure representativeness (Ellis and Freeman 2004, Ellis and Mdoe 2003, Vyamana 2009, Ravnborg 2003). Prior to interviewee selection, we conducted participatory wealth ranking in each village, following the procedure described by Ravnborg (2003) and Vyamana (2009). We asked Village Council members to provide a list of charcoal producers in their village. Then, we organized a workshop with village representatives from all sub-villages, whom we asked to rank producers by socio-economic wealth status, and used the list of charcoal producers by wealth category (i.e. poorest, poor, non-poor) to stratify the sample of interviewed charcoal producers (Table 1).

**Table 1.** Sampling size per wealth category with sub-totals for OA-villages and CB-villages. Other = Charcoal producers for which a wealth status could not be derived before the interview.

| | | **Number of respondents interviewed per wealth category** | | | | |
|---|---|---|---|---|---|---|
| | | **Poorest** | **Poor** | **Non-poor** | **Other** | **Total** |
| **CB-villages** | *V1* | 13 | 24 | | | 37 |
| | *V2* | 20 | 8 | | | 28 |
| | *V3* | 9 | 17 | | | 26 |
| | **Sub-total** | 42 | 49 | | | 91 |
| **OA-villages** | *V4* | 16 | 12 | | | 28 |
| | *V5* | 9 | 6 | | 1 | 16 |
| | *V6* | 11 | 10 | 1 | 3 | 25 |
| | **Sub-total** | 36 | 28 | | 4 | 69 |
| **Grand total** | | 78 | 77 | 1 | 4 | 160 |

We developed a survey to collect data on social interactions among charcoal producers and between charcoal producers and members of governance agencies (i.e., Village Council, District government and TFS). We asked interviewees for the names and surnames of charcoal producers and members of governance agencies they interact with. In case interviewees mentioned interactions with specific members of agencies but did not remember their names, this was noted down. We also derived the quality of interactions between charcoal producers themselves and their governments, measured as the (i) level to which charcoal producers feel supported by their fellow villagers, the Village Council, the District government, and TFS, and (ii) number of interactions between charcoal producers per week and between charcoal producers and Village Council members per month (Table 2). We specifically did not specify or define support in the surveys, as we did not wish to interpret these feelings for them. Instead, we asked about general feelings of support, e.g., through the question "Do you feel supported by the District Council?". Finally, we obtained information on the formality of interactions, measured as (i) membership to charcoal producer associations (and other associations) and (ii) as the diversity of interactions, i.e., whether they producers mainly with relatives, neighbors or other types of producers (Table 2). We decided not to include interactions with TFCG in our analysis because they had left the villages at the time of our study and did not play a role in forest governance anymore.

**Table 2.** Indicators of formality and quality of interactions between people in the charcoal production system.

| | **Indicator** | **Indicator type** | **Rationale for adding the indicator** |
|---|---|---|---|
| **Quality of interactions** | *Social interactions per week / month* | Bonding and linking, per-node | ❖ *Mechanism*: A higher number of interactions per week / month results in more exchange of knowledge and understanding of the production system by those involved (Noorderhaven and Harzing 2009). The number of interactions is likely more frequent between producers (i.e. on a weekly basis) than with members of governance agencies (i.e. on a monthly basis) (Kawamoto and Kim 2019).<br>❖ *Interpretation*: Higher values indicate high quality interactions, while lower values indicate poor quality interactions. |
| | *Feeling supported by other villagers* | Bonding, per interviewee | ❖ *Mechanism*: Other villagers could provide support by buying, selling, establishing connections that will benefit the charcoal producers (Jensen and Jetten 2015).<br>❖ *Interpretation*: Charcoal producers who feel supported by other villagers are assumed to experience higher quality bonding interactions than those who do not feel supported. |

| | | | |
|---|---|---|---|
| | *Feeling supported by the Village Council* | Linking, per interviewee | ❖ *Mechanism*: Connections with the Village Council members could enable more trust, better monitoring of charcoal activities and more support for the marketing of charcoal production (Dahal and Adhikari 2008).<br>❖ *Interpretation*: Charcoal producers who feel supported by their Village Council are assumed to experience higher quality linking interactions than those who do not feel supported. |
| | *Feeling supported by the District Government* | Linking, per interviewee | ❖ *Mechanism*: Connections to the District government may ease the acquisition of permits, compliance with Federal and District regulations, create an avenue to communicate concerns to members of higher governance levels, and allow charcoal producers to check compliance to institutions, such as the Tanzanian forest act (Campbell 1996a).<br>❖ *Interpretation*: Charcoal producers who feel supported by their District Council are assumed to experience higher quality linking interactions than those who do not feel supported. |
| | *Feeling support by the Tanzania Forest Service* | Linking, per interviewee | ❖ *Mechanism*: Connections to the Forest Service may enable better compliance with Federal regulations and allow charcoal producers to check compliance to institutions, such as the Tanzanian forest act (Arts and Vissen-Hamakers 2012).<br>❖ *Interpretation*: Charcoal producers who feel supported by Tanzania Forest Service are assumed to experience higher quality linking interactions than those who do not feel supported. |
| **Formality of interactions** | *Access to charcoal producer association* | Bonding, per interviewee | ❖ *Mechanism*: Associations provide a way to support charcoal producers by exchanging information, providing a platform to market accessibility, dissemination of activities, new technologies and training as well as providing support to the individual charcoal producers (Fabricius and Collins 2007, Maas *et al* 2014).<br>❖ *Interpretation*: High levels of membership to charcoal producer associations enhances the formality of interactions between charcoal producers themselves and with their village council. |
| | *Access to other associations* | Bonding, per interviewee | ❖ *Mechanism*: Associations provide a way to support charcoal producers by exchanging information, providing a platform to market accessibility, dissemination of activities, new |

| | | | |
|---|---|---|---|
| | | | technologies and training (Fabricius and Collins 2007, Maas *et al* 2014).<br>❖ *Interpretation*: High levels of membership to other associations indicates potential of formalization of charcoal producer interactions. |
| | *Family, neighbors or others* | Bonding and linking, per-node | ❖ *Mechanism*: Family and neighbors provide support, including support in terms of employment, security, time, and knowledge (Cofré-Bravo *et al* 2019).<br>❖ *Interpretation*: We consider interactions between family members least formal, interactions between neighbors more formal them interactions between family members and interactions with others (i.e., non-family/neighbor) formal interactions. |

The survey used in this study was developed for a larger project, and also included other questions. In this study, we focused on Sections 9, 11, 13, 14 and 15 of the survey; remaining information was used for interpretation (Appendix A). To reduce risks of misinterpretation due to cultural and language differences, the surveys were translated and conducted in Swahili by Tanzanian co-authors and were iterated with other authors prior to the fieldwork. We first conduced a pilot study to test the surveys by interviewing three people in a village that was not part of our study area, allowing for final survey adjustments. Prior to all interviews, we acquired permission to conduct surveys during a Village Council meeting with Village Council members, one District government representative and, in CB-villages, representatives of charcoal producer associations. We asked all interviewees to sign an ethics-and-responsible-research-consent-form translated into Swahili (Appendix B). We asked interviewees for permission to be recorded. In case interviewees were illiterate, a literate guide read the consent form aloud to interviewees to communicate its content and asked interviewees for their oral consent. In case interviewees were reluctant to be recorded or to answer specific questions, no recordings were made and/or questions were skipped on the survey. All interviewees were informed that they could opt out of the study at any point in time.

We conducted fieldwork during the Covid-19 pandemic. Travel restrictions due to Covid-19 prevented the lead and senior author to conduct fieldwork in person in Tanzania. We consulted with the field team to ascertain that the field surveys could be conducted given country restrictions, personal exposure and ethical considerations. All field team members consented to surveying under these conditions, given the yet restricted incidence of Covid-19 cases, their commitment to the research and the job opportunities it provided them and the communities. All villages were asked for their consent during Village Council meetings. Upon agreement, we conducted surveys under protective measures to guard health of participants during Village Council meetings, interviews, and daily activities of the field researchers, to prevent further spread of Covid-19. For this purpose, masks and hand sanitizer were provided, interviewees and interviewers maintained a 1.5 m distance as regulated, and masks were disposed into provided garbage cans.

### 2.3 Social network metrics

We used the survey data to map the network structure of each of the six study villages to examine their bonding and linking. We used information on names and surnames of charcoal producers and Village Council members that producers work and interact with in their village. We anonymized records by numbering each charcoal producer and member of the Village Council to create an edge (i.e., interaction) and node (i.e., person in the network) list. Because interviewees often did not remember names and surnames of members of the District government and TFS, we did not add these members to the networks. Instead, we recorded whether or not charcoal producers mentioned interactions with members of their District government and TFS, and if so with how many, not to affect our linking estimates.

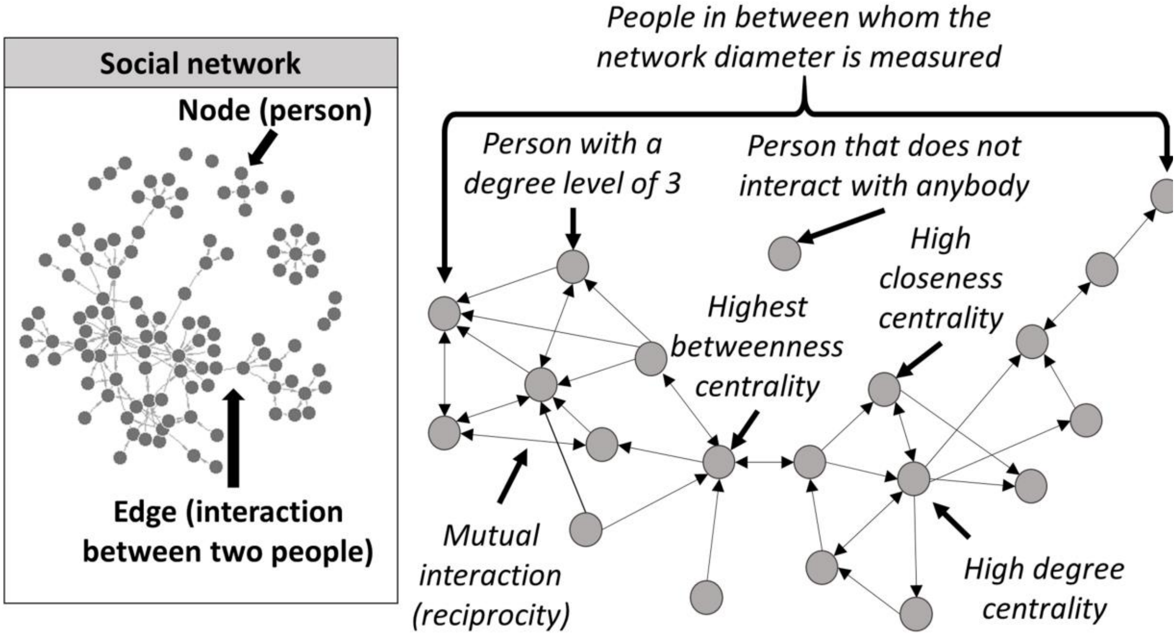

**Figure 2.** Social network analysis components and metrics, description of social networks (nodes and edges) and metrics chosen (an explanation of each metric can be found in Table 3).

To describe the structure and characteristics of each network, we computed a series of network metrics (Fig. 2, Table 3). We calculated two types of metrics, (i) per-node (degree, closeness centrality and betweenness centrality), and (ii) per-network (diameter, distance and reciprocity). Per-node metrics measure the number of interactions that occur between producers themselves and with members of their Village Council, the density of direct and indirect interactions, and the level of influence each charcoal producer has over others. Taken together, per-node metrics provide an indication of bonding and linking in each of the study villages, allowing for comparison. The per-node measures of bonding and linking allowed us to make inferences about network heterogeneity and decentralization. In contrast, per-network metrics provide an indication of network size and interaction density between charcoal producers themselves and their Village Council members across the entire network. These per-network metrics indicate bonding and linking density in the network, i.e., how closely all people in the network interact with each other.

**Table 3.** Network metrics used to describe the network characteristics of charcoal producers. The metrics are visualized in Figure 2.

| | **Metrics** | **Description** | **Explanation of and rationale for including the metric** |
|---|---|---|---|
| **Per-node metrics** | *Degree* | Number of interactions a person has with other people | ❖ *Explanation*: Degree is a measure of how much a specific person interacts with other people in the network, and the variation in degree between people provides an indication of the density of the network. The more interactions charcoal producers have with each other and with members of governance agencies, the higher their bonding and linking social capital.<br>❖ *Rationale*: We expect a relatively lower degree in OA-villages than in CB-villages |

|  |  |  |  |
|---|---|---|---|
|  |  |  | because charcoal production in rural communities is traditionally carried out by individuals or small groups of producers in open access systems (Baumert *et al* 2016, FAO 2017), but requires significantly more interactions and cooperation under the participatory harvesting and decision-making regimes implemented under CBNRM (Ishengoma *et al* 2016). Additionally, charcoal production is often carried out illegally in open access regimes, which might reduce trust between charcoal producers, likely limiting the number of producers and members of institutions they interact with (Bolognesi *et al* 2015, Mapese *et al* 2013). |
|  | *Closeness centrality* | A measure of how far a person is located from all other people in the network on average (inverse distance) | ❖ *Explanation*: Closeness centrality is a measure of how central a person is located within the network and the variation in closeness centrality between people provides an indication of how evenly social interactions and connections are distributed among people. For instance, if there is one charcoal producer with a large closeness centrality, while all other people have a low closeness centrality, that charcoal producer has a very important role in the network, connecting many people in the network.<br>❖ *Rationale*: We expect higher closeness centralities for charcoal producers operating in CB-villages than in OA-villages because producers in CB-villages likely interact with more people within the network (see Degree), densifying the network and causing an more even distribution of interactions and connections than in OA-villages. Hereby, we expect multiple producers with a relatively high closeness centralities in CB-villages, because the TTCS project, and CBNRM in general, strives for decentralized forest management (Becker 2001, Ishengoma *et al* 2016). |
|  | *Betweenness centrality* | Number of shortest paths between people that pass through a particular person | ❖ *Explanation*: Betweenness centrality is a measure of how many people a person directly and indirectly influences in the network. Charcoal producers and members of governance agencies with a high betweenness centrality have a lot of influence over other people in the network and their interactions, providing a bridge between two or more communities of people that closely interact with each other.<br>❖ *Rationale*: In OA-villages, multiple betweenness centrality scenarios may |

| | | | |
|---|---|---|---|
| | | | occur. On the one hand, it is likely that betweenness centrality is low for all charcoal producers, as we expect limited numbers of interactions. On the other hand, it could be that a central figure arises in the charcoal producer networks of OA-villages, which has a high influence over producers because of a certain (informal) authority over the charcoal production activity, e.g., a Village Council member. In contrast, we expect a relatively large number of charcoal producers with high levels of betweenness centrality in CB-villages, as the TTCS project, and CBNRM in general, strives for decentralized forest management in which multiple people have influence over others, not only one central figure (Becker 2001, Ishengoma *et al* 2016). |
| **Per-network metrics** | *Diameter* | Shortest distance between the two most distant persons in the network | ❖ *Explanation*: The diameter of a network provides both an indicator of the size of the network, as well as how closely people are connected to each other within the network. The larger the diameter of a charcoal producer network, the more charcoal producers stand between one producer at the far end of the network and another producer at the far end of the network.<br>❖ *Rationale*: In OA-villages two diameter scenarios may occur. On the one hand, we may expect a relatively high diameter in OA-villagers because of a relatively low network density caused by limited interactions and low evenness in the distribution of interactions, which causes the distance between the two most distant persons in the network to increase. On the other hand, we may expect relatively small bonding and linking networks in OA-villages compared to CB0-villages, in which charcoal producers operate individually or in small disconnected groups (e.g., groups of two or three persons, which are disconnected from other small groups). The latter scenario results in a relatively low diameter, as it is measured as the amount of edges between the two most distant persons in the network. Whereas bonding and linking networks in CB-villages are expected to be relatively dense due to high degree, closeness centrality and betweenness centrality, which likely result in a relatively low diameter, the network sizes are possibly larger than those of OA-villages. Hence, due to their relatively large network size, the diameter of CB-networks is likely higher than that of OA-networks. |

| | | | |
|---|---|---|---|
| | *Distance* | Average number of steps along the shortest paths for all possible pairs of people in the network | ❖ *Explanation*: The distance of a network is quite similar to the diameter but takes all people within the network into account, instead of just those at the far end of the network. The bigger the distance of a charcoal producer network, the less direct connections there are between charcoal producers and the broader the network.<br>❖ *Rationale*: We expect similar scenarios for distance as for diameter in OA-villages and CB-villages. However, whereas we expect a relatively constant distance for CB-villages following bootstrapping because of a higher number and densities of connections, we expect the distance to variate in OA-villages, because bootstrapping may alter the average number of steps along the shortest paths substantially within low density networks with small disconnected communities, as there are likely limited possible pairs of people within OA-networks. |
| | *Reciprocity* | The likelihood of people in the social network to be mutually connected | ❖ *Explanation*: The reciprocity of a network provides an indication of whether interactions are perceived by only one person or by the person they interact with as well. In this study it provides an indication of whether the charcoal producers interact with each other and mention each other's names or whether they interact with other charcoal producers that were not interviewed for this study.<br>❖ *Rationale*: We expect a higher likelihood that charcoal producers are mutually connected in CB-villages than in OA-villages because of the formal facilitation of interactions through charcoal producer associations and participatory forestry schemes under CBNRM, which causes producers the interact and work with a higher number of people and may enhance the likelihood that charcoal producers mention each other in interviews. However, for linking we expect low reciprocity for both CB-villages and OA-villages, as we only interviewed charcoal producers and limited charcoal producers are part of the Village Council. Of all metrics, we expect that reciprocity is most affected by the methodology adopted for this study, in particular for linking, as we were unable to interview all charcoal producers operating in each village and did not ask Village Council members with which charcoal producers they interact with, except if they produced charcoal themselves. |

### 2.4 Social network analysis

We tested for statistical differences in bonding and linking in OA-villages and CB-villages using the network metrics. First, we assessed the normality of per-node metrics distribution, using the Shapiro-Wilk test and histograms. Per-node metrics were not normally distributed and no normal distribution could be derived through transformation. Thus, we used the non-parametric Kruskal-Wallis test to assess differences in per-node metrics per village and between all villages (Breslow 1970). Second, we compared per-node metrics of poor and poorest charcoal producers to determine effects of wealth status. As only one non-poor producer was interviewed, we did not compare this producer to poor and poorest wealth classes.

Because we only analyzed six villages, we could not directly compare per-network metrics of CB-villages with OA-villages. Instead, we assessed the robustness of the network structure between villages, using a bootstrapping approach to obtain a distribution of per-network metrics. We kept the degree distribution (i.e., number of interactions per node) of the networks constant and swapped edges, rewiring edges 10x at random to allow the number of iterations to approach 100%. We did this 1000x to obtain 1000 results for each per-network metric. Because bootstrapped per-network outcomes were normally distributed and assured sufficient degrees of freedom, we used a pairwise t-test to determine whether per-network metrics on average differ across villages. To further test network robustness to node removal, we bootstrapped each network 1000x, for each iteration removing 3 nodes and their respective edges, using the R-function “delete_vertices”.

We derived the number of network communities, i.e., a subset of people within the network that more densely interacts with each other than with other people in the network, to assess connectedness between different parts of the network as indicators of decentralization and heterogeneity. We used the function “cluster_walktrap” in R (Csardi and Nepusz 2006), which finds communities within social networks by measuring “walks” between nodes along their edges and compares the distribution of these walks with those produced at random. When walks between nodes are shorter than randomly expected, a community is identified. The random walks depend on edge weights, which represent costs of traveling a specific edge in the network. Edges that prolong the random walk to other network regions have a lower edge weight than edges that are centrally located and allow for fast random walks. Larger edge weights increase the probability that the random walker randomly selects an edge and, therefore, correspond to stronger connections. The number of steps each random walk should take per walk was set at 4 (default setting), which allowed for variations in walks in dense networks, as those expected for CB-villages.

### 2.5 Quality and formality of interactions

We qualitatively compared the outcomes for all interaction quality and formality indicators between CB-villages and OA-villages to explain the results of social network indices. We repeated the analysis to compare between poorest and poor charcoal producers.

We conducted all data analyses in R (Team 2019), using the packages “stats”, “igraph” (Csardi and Nepusz 2006), and “network” (Butts 2008).

## 3. Results

### 3.1 Bonding networks

We find stronger bonding in CB-villages than OA-villages, i.e., more connections between charcoal producers (orange dots in Fig. 3), and higher numbers of communities (i.e., a subset of people within the network that more densely interacts with each other than with other people in the network, to assess connectedness between different parts of the networks as indicators of network decentralization and heterogeneity) in CB-villages, ranging from 8 to 14 communities, which are nested. In OA-villages, we observe fewer communities, only 1 or 2, which are connected to each other. More charcoal producers are members of the Village Council (blue dots in Fig. 3) in CB-villages than in OA-villages.

We find significantly higher network degree in all CB-villages than in OA2 and OA3 (Fig. 4); in other words, in CB-villages charcoal producers have generally more interactions than in OA-villages. Additionally, charcoal producers in both CB1 and CB3 interact with significantly more charcoal producers than in OA1. We find significantly higher betweenness centrality in CB-villages than OA-villages, suggesting that few producers in OA-networks have much influence over other producers. In contrast, we find a significantly lower closeness centrality in CB-villages than in OA2 and OA3, and a significantly lower closeness centrality in CB1 and CB2 than OA1, indicating higher evenness in

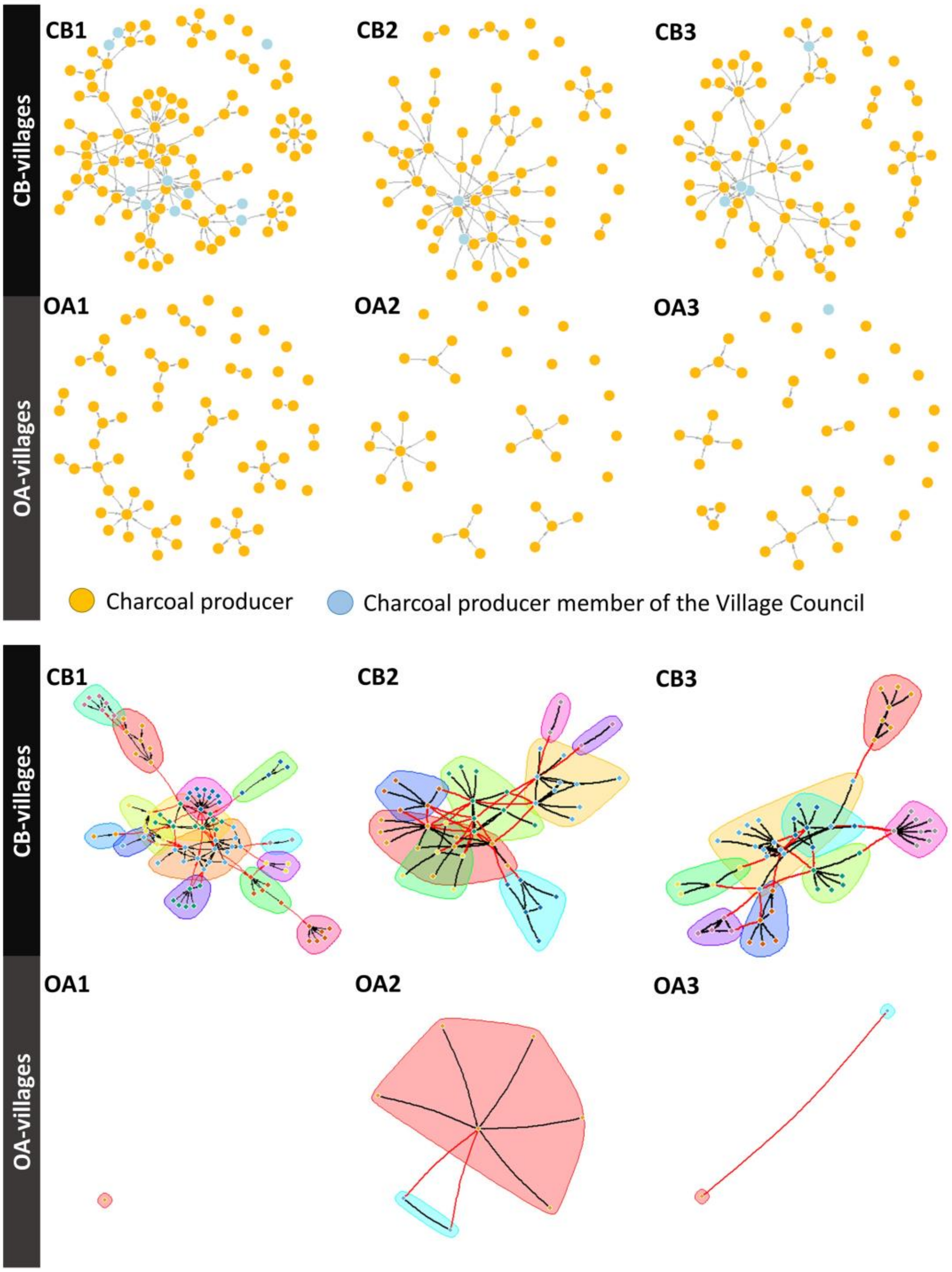

**Figure 3.** *Top panel*: Bonding social networks of charcoal producers with each other in CB-villages (CB1-3) and OA- villages (OA1-3). The blue nodes represent charcoal producers that both produce charcoal and are members of the Village Council. *Bottom panel*: Communities, i.e. subsets of charcoal producers that more densely interact with each other than with other charcoal producers.

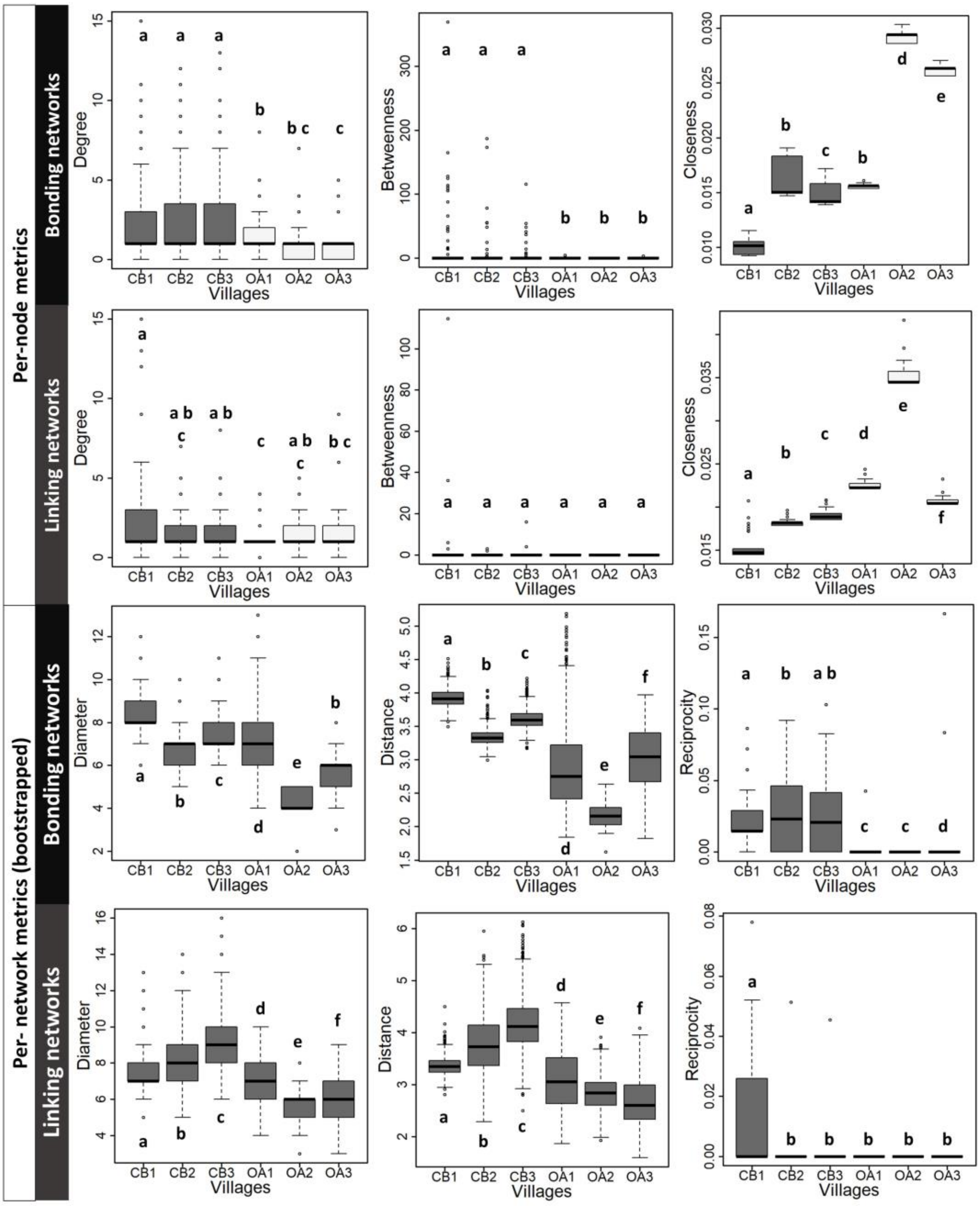

**Figure 4.** *Top panel*: Three per-node network metrics (i.e., degree, betweenness centrality and closeness) for all six villages in the study area. *Bottom panel*: Three bootstrapped per-network metrics (i.e., diameter, distance and reciprocity) for all six villages in the study area. Statistics can be found in Appendix Table C1 and C2.

interaction distribution in CB-villages. We do not find statistical differences between poor and non-poor charcoal producers (Appendix Fig. C1). All statistics for comparison of bonding network metrics across villages can be found in Appendix Table C1.

The bootstrap results show significantly higher network diameters for CB1 and CB3 than for OA-villages (Fig. 4). The diameter of CB1 is significantly higher than that of CB2 and CB3. The diameter of all OA-villages is significantly different from each other; highest for OA1, followed by OA3 and OA2. The distance, or the number of steps along the shortest paths between nodes is significantly higher for CB-villages than OA-villages (Fig. 4), and distance differs significantly between all villages. Finally, reciprocity is significantly higher in CB-villages than in OA-villages (Fig. 4). The reciprocity of CB1 and CB2 does not differ significantly from OA3.

### 3.2 Linking networks

CB-villages show stronger linking than OA-villages (Fig. 5), i.e., more connections between charcoal producers (orange dots) and Village Council members (black dots) in CB-villages than OA-villages. However, differences in linking between CB-villages and OA-villages are less strong (Fig. 3). Overall, OA-villages show higher linking than bonding, while CB-villages show higher bonding than linking for closeness centrality, diameter, distance and reciprocity per village (Fig. 4, Table 4). We also find significant differences in betweenness centrality between the linking and bonding networks of CB-villages. We observe between 6 to 11 nested communities in CB-villages, a slightly lower number than for bonding networks. More communities are formed in linking networks of OA-villages than in their bonding networks, namely 3 or 4 communities. All statistics for comparison of linking metrics across villages can be found in Appendix Table C2.

**Table 4.** Statistical differences between per-node-metrics and bootstrapped per-network metrics for bonding and linking networks reported as p-values and in the case of per-node metrics combined with Kruskal-Wallis chi-squared values. CB1-CB3 represent villages under the CBNRM project Transforming Tanzania's Charcoal Sector (TTCS), while OA1-OA3 represent villages under open access. Betweenness levels are 0 for each node for both bonding and linking of OA2.

| | **Per-node metrics** | | | **Per network metrics** | | |
|---|---|---|---|---|---|---|
| | *Degree* | *Betweenness centrality* | *Closeness centrality* | *Diameter* | *Distance* | *Reciprocity* |
| *CB1* | $X^2_{(1, x = 177)} = 0.36$<br>P-value = 0.5494 | $X^2_{(1, x = 177)} = 4.03$<br>P-value = 0.0448* | $X^2_{(1, x = 177)} = 127.13$<br>P-value = < 2.2e-16*** | P-value = <2e-16*** | P-value = <2e-16*** | P-value = 2.3e-05*** |
| *CB2* | $X^2_{(1, x = 124)} = 3.45$<br>P-value = 0.0631 | $X^2_{(1, x = 124)} = 6.36$<br>P-value = 0.0117* | $X^2_{(1, x = 124)} = 19.91$<br>P-value = 8.1e-06*** | P-value = <2e-16*** | P-value = <2e-16*** | P-value = <2e-16*** |
| *CB3* | $X^2_{(1, x = 126)} = 2.33$<br>P-value = 0.1268 | $X^2_{(1, x = 126)} = 7.69$<br>P-value = 0.0056* | $X^2_{(1, x = 126)} = 93.52$<br>P-value = < 2.2e-16*** | P-value = <2e-16*** | P-value = <2e-16*** | P-value = <2e-16*** |
| *OA1* | $X^2_{(1, x = 112)} = 0.89$<br>P-value = 0.3462 | $X^2_{(1, x = 112)} = 2.05$<br>P-value = 0.1521 | $X^2_{(1, x = 112)} = 83.93$<br>P-value = < 2.2e-16*** | P-value = 0.8700 | P-value = 5.2e-16*** | P-value = 0.7900 |
| *OA2* | $X^2_{(1, x = 64)} = 0.69$<br>P-value = 0.4075 | NA | $X^2_{(1, x = 64)} = 19.74$<br>P-value = 1.8e-12*** | P-value = <2e-16*** | P-value = <2e-16*** | P-value = 1.0000 |
| *OA3* | $X^2_{(1, x = 89)} = 3.72$<br>P-value = 0.0537 | $X^2_{(1, x = 89)} = 1.23$<br>P-value = 0.2684 | $X^2_{(1, x = 89)} = 68.41$<br>P-value = < 2.2e-16*** | P-value = 1.6e-09*** | P-value = <2e-16*** | P-value = <2e-16*** |

* p-value = <0.05, ** p-value = <0.005, *** p-value = <0.0005

We observe significantly higher degree levels in CB1 than in OA1 and OA3 (Fig. 4). We also observe significantly higher degree in CB3 than OA1. We found no significant difference in betweenness centrality in linking networks (Fig. 4). CB-villages have a significantly lower closeness centrality than OA-villages, and the closeness centrality significantly differs between all villages. Bootstrap results reveal a significantly higher diameter of linking networks in CB-villages than OA-villages. Overall network diameter differs significantly across villages, indicating differences in network size and density (see Table 3). Similar results were obtained for distance. The reciprocity of CB1 is significantly higher than that of all other villages. We do not find statistical differences between poor and non-poor charcoal producers (Appendix Fig. C1).

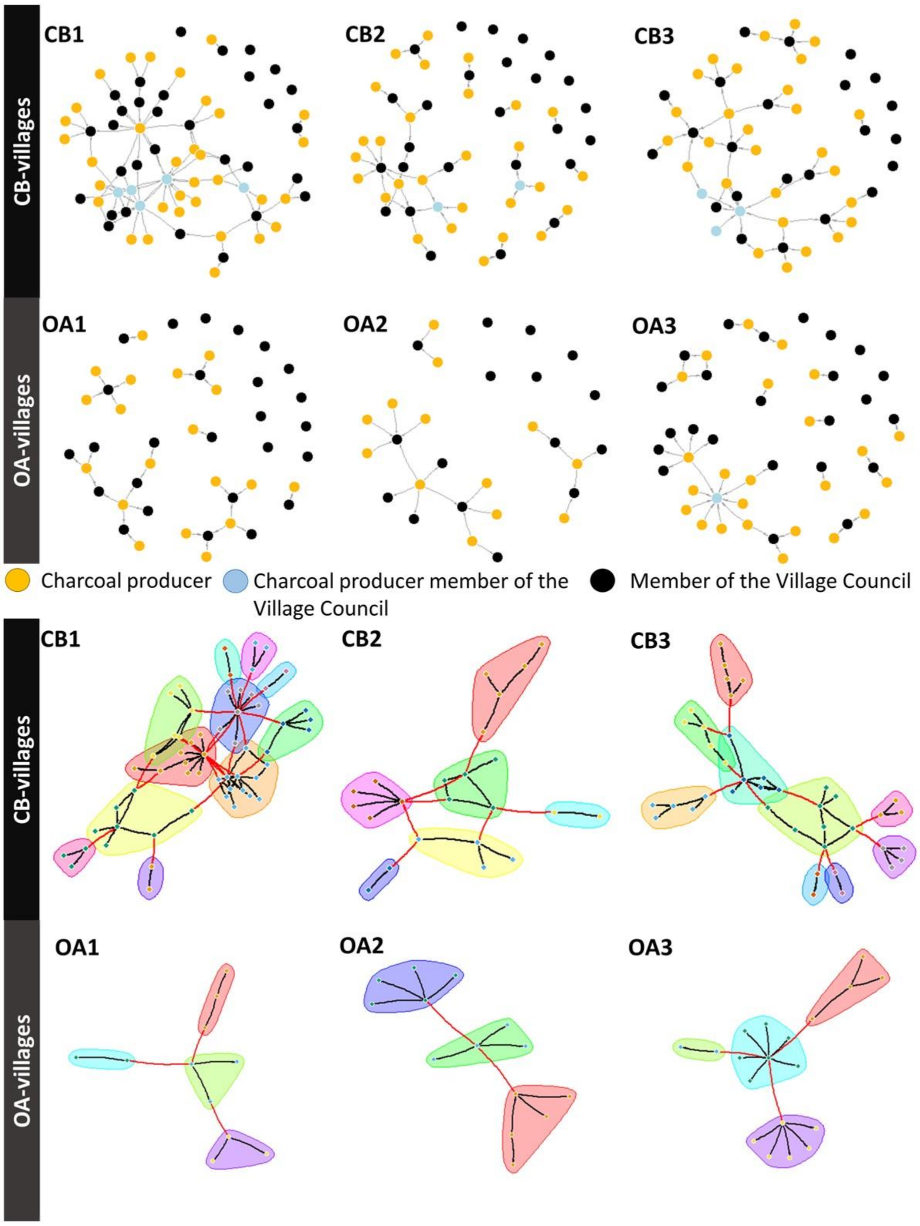

**Figure 5.** *Top panel*: Linking social networks, i.e., interactions of charcoal producers with members of their Village Council CB-villages and OA-villages. The blue nodes represent those charcoal producers that both produce charcoal and are a member of the Village Council, the black nodes represent the charcoal producers that were interviewed and the yellow nodes the members of the Village Council they interact with. *Bottom panel*: Communities within linking social networks, i.e., subsets of charcoal producers and members of the Village Council that more densely interact with each other than with other charcoal producers and members of the Village Council in the network.

In both village types, the majority of charcoal producers does not interact with Kilosa District government members and TFS. In CB1 four charcoal producers interact with up to three District members, in CB2 three charcoal producers interact with up to three District members, and in CB3 three charcoal producers interact with up to two District members. This is relatively higher than for OA-villages; only in OA1 one charcoal producer interacts with four district members. The same pattern is observed for interactions with TFS, with two charcoal producers interacting with up to four TFS members in CB1, four charcoal producers interacting with up to three members in CB2, and two charcoal producers with up to two members in CB3. Only in OA1, one charcoal producer interacts with one TFS member. Charcoal producers interacting with District or TFS members are not part of the Village Council.

### 3.4 Robustness of social networks

Both bonding and linking charcoal producer networks are relatively robust to edge swapping, i.e., we find limited variation in per-network metrics upon edge swapping (Fig. 4). We find largest variations in reciprocity for CB-villages. Both bonding and linking networks are also relatively robust to node removal, i.e., we find limited variation in per-network indices upon node removal (Fig. 6). Edge swapping and node removal result in comparable and relatively higher diameter and distance values observed for CB-villages compared to OA-villages. However, upon node removal, we find larger variations in distance for OA1 and reciprocity for OA3 for bonding, and diameter for OA2, distance for CB3 and OA3, and reciprocity for CB1 for linking than in other villages.

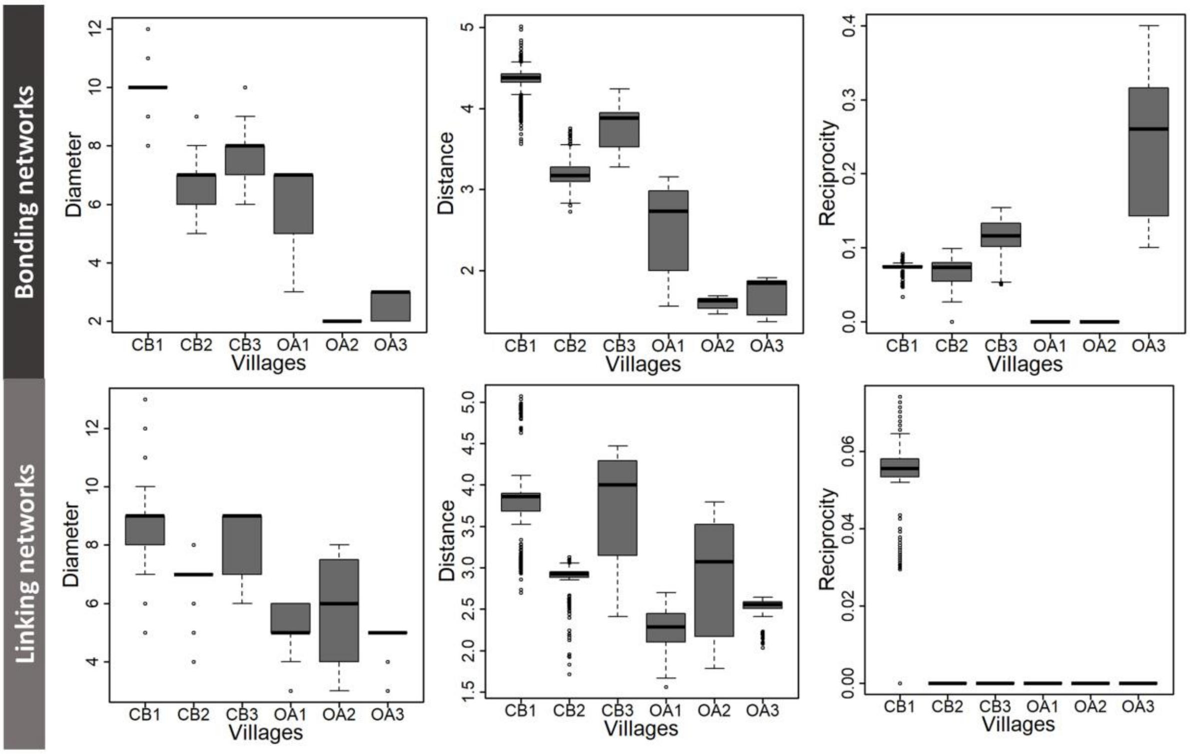

**Figure 6.** Robustness of the networks. We observe that CB-villages are more resilient to node removal than OA-villages because they show less variation in diameter, distance and reciprocity. Bonding networks reflect the interactions of charcoal producers with each other, while linking networks reflect the interactions of charcoal producers with members of the Village Council.

### 3.5 Formality of interactions

In CB-villages, a large percentage of charcoal producers are part of a charcoal producer association (68% to 96%; Fig. 7), and those involved in other associations make up smaller fractions. In OA-villages, only 1 charcoal producer indicated to be a member of a charcoal producer association, while the fraction in other associations is higher. We do not observe differences between wealth classes (Appendix Fig. C2). We found no clear pattern in the type of interactions, whether with family members, neighbors or other producers.

### 3.6 Quality of interactions

Charcoal producers in general experience relatively high support from other villagers (including other charcoal producers), ranging between 61% and 84% (Fig. 7), and we find no significant differences between CB-villages and OA-villages. Poor charcoal producers report relatively stronger feelings of support by other villagers than poorest charcoal producers, except in CB1 (Appendix Fig. C3). Reported support by Village Council members is lower than reported support from villagers in general, ranging between 39% and 65%. Here, poor charcoal producers also report relatively higher support from their

Village Council than the poorest charcoal producers (Appendix Fig. C3). The exception is OA1, where 62% of the poorest charcoal producers report that they feel supported by the Village Council in contrast to 42% of the poor charcoal producers. Charcoal producers generally report relatively low support by the District Government and TFS, ranging between 0% and 22%. Support experienced from TFS is relatively lower in OA-villages (0%-4%) than in CB-villages (11%-15%) and support from the District government is also relatively lower in OA-villages (0%-13%) than that of CB-villages (14%-19%).

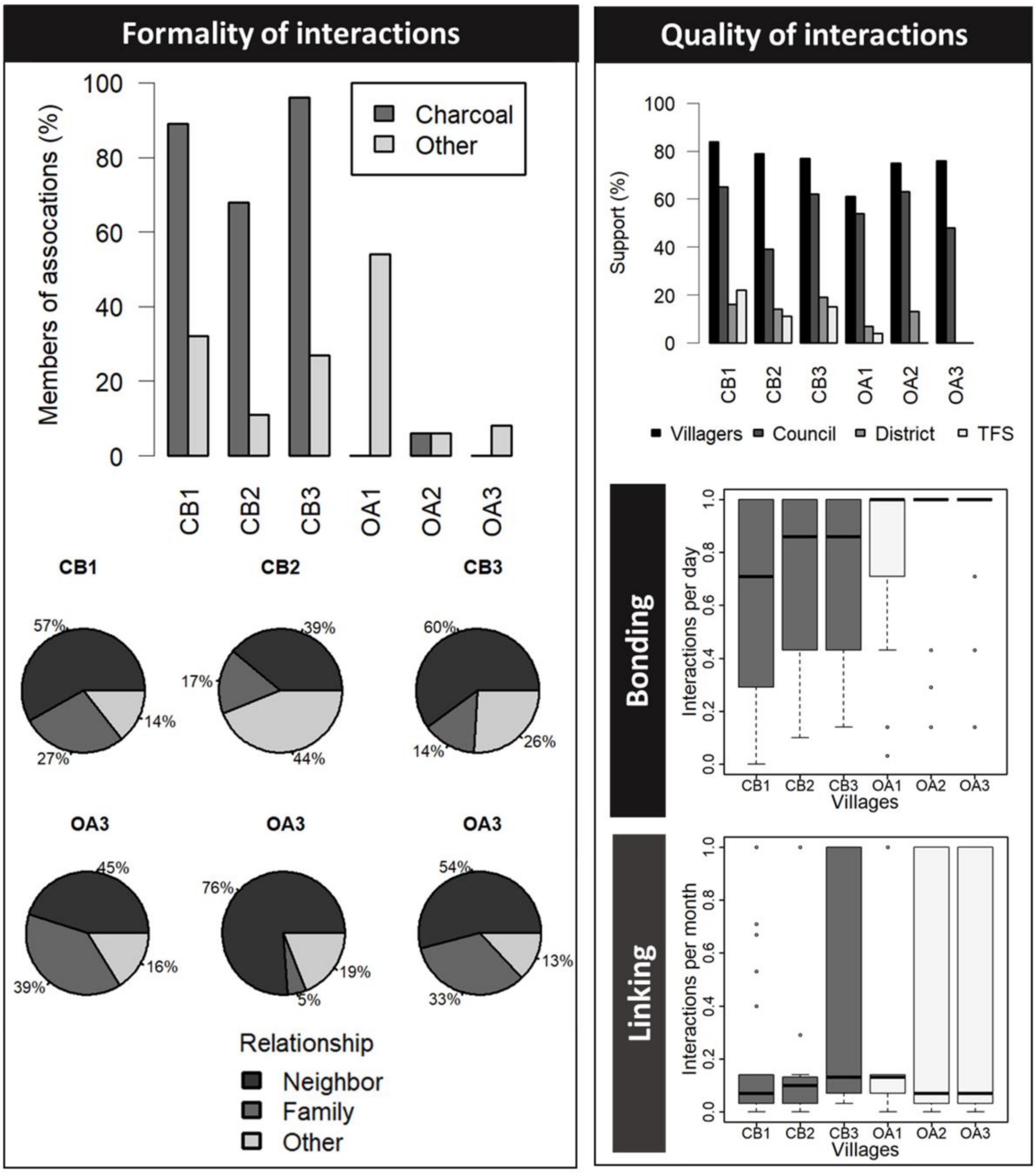

**Figure 7.** Formality and quality of charcoal producer interactions. The pie-charts show the percentage interactions the charcoal producer has to other charcoal producers (bonding capital). The associations include charcoal producer associations and other types of associations, such as agriculture or credit associations. Feelings of support indicate how much support charcoal producers get from other villagers, their Village Council, the District Government and the Tanzania Forest Service (TFS). The two boxplots on interaction intensity reflect the amount of times charcoal producers interact with (i) other producers (bonding capital), and (ii) members of the village government (linking capital). CB-villages are those in which the CBNRM project Transforming Tanzania's Charcoal Sector (TTCS) has been introduced and OA-villages are open access villages.

We find relatively lower and more variable interaction frequency between charcoal producers per day in CB-villages than OA-villages (Fig. 7). The majority of charcoal producers in CB-villages interacts between 0.4 to 1 time a day, while the majority charcoal producers in OA-villages interacts daily (between 0.7 and 1 times a day in OA1). Finally, interaction intensity between charcoal producers and members of the Village Council is relatively lower in CB1, CB2 and OA1. In CB3, OA2 and OA3 the interactions range from monthly to rarely (i.e., once every 4 to 6 months).

## 4. Discussion

We find differences in network structure between open access and CBNRM villages, with CBNRM communities showing higher bonding and some higher linking, as revealed by their dense decentralized networks with multiple nested sub-communities. These results support our expectations that CBNRM results in decentralization and heterogeneity in networks (Massoi and Norman 2009), as well as higher interconnectedness between charcoal producers and members of governance agencies (Campbell & Shackleton, 2001; Schnegg, 2018). This indicates that CBNRM of charcoal production meets the important objective to foster dense collaboration and decision-making.

### 4.1 Social network characteristics

#### *4.1.1 Bonding networks*

The observed higher bonding of charcoal producer networks in CBNRM communities matches the expectation that formalization of interactions results in denser networks (Becker 2001). On the one hand, high density networks enable community resilience because loss of one charcoal producer in high density networks is less disruptive than in low density networks. This is expected to increase feelings of belonging, potentially enhancing trust (Bhandari and Yasunobu 2009, Nooteboom 2007), as well as the fostering of shared norms and values and knowledge exchange among charcoal producers (Bhandari and Yasunobu 2009, Nooteboom 2007). On the other hand, a dense network may hinder development, as it reduces heterogeneity and thus limits innovation (Bodin and Crona 2009). High bonding under CBNRM contrasts with the relatively larger network diameters in CB-villages than in OA-villages, which may indicate some individualism under CBNRM. Large network diameters result from the many sub-communities, which could result from explicit efforts by the TTCS project to reach out to marginalized groups, which in turn explains limited differences between poor and poorest producers. Alternatively, small network diameters in OA-villages may result from few disconnected groups of producers. Overall, high bonding combined with a relatively large network diameter may provide advantages for CB-villages, as it puts charcoal producers in direct and indirect contact with people operating in different sub-communities, potentially enhancing knowledge exchange (Bodin and Crona 2009).

Besides densification, we also observe higher decentralization of social networks in CB-villages than in OA-villages, i.e., a relatively higher variation in betweenness centrality in CB-villages than OA-villages, which is in line with our hypothesis. High variation in betweenness centrality shows that multiple charcoal producers have influence over other charcoal producers, irrespectively of their Village Council membership. This may be because many people under the TTCS project decide upon charcoal production locations and quantities, and from active monitoring of charcoal production by the VNRC (Ishengoma *et al* 2016). Further, the TTCS project aims for shared-decision making through charcoal producer associations, which interact with the Village Council and VNRC (Ishengoma *et al* 2016), as well as for informal charcoal producer group formation. This active encouragement of shared decision-making among different hierarchical levels may enhance both interaction numbers between producers themselves and with their Village Council members. Although low variations in betweenness centrality in OA-villages suggest that few to no charcoal producers have a high influence over others, this may result from misidentification of influential people by path-measure metrics (Guilbeault and Centola 2021). Future studies may include novel social network metrics to identify influential charcoal producers in OA-villages, such as complex path length and complex centrality metrics (Guilbeault and Centola 2021).

#### *4.1.2 Linking networks*

Although we observe a larger diameter and distance in linking networks of CB-villages compared to OA-villages, the number of interactions between charcoal producers and members of their village government does not differ. This finding that CBNRM has a bigger influence on bonding than on linking contrasts with our hypothesis. The results suggests challenges in the integration of charcoal producers in Village Council decision-making or forest monitoring. It could be that linking requires or produces substantially less interactions due to fewer or more efficient meetings, while bonding requires more interactions because of forest monitoring and collective charcoal production. Contrary to our hypothesis, we find higher linking than bonding in open access systems. This could be the result of low levels of trust between charcoal producers and the relatively individual nature of charcoal production activities (Baumert *et al* 2016, Butz 2013). Limited linking between charcoal producers, District and TFS members in all villages is surprising because closer collaborations with the District government should occur in CB-villages as a result of the CBNRM scheme in place (Ishengoma *et al* 2016, Doggart 2016).

Similarities in the number of interactions and betweenness levels in bonding and linking networks counter our expectations that charcoal producers interact more with people of comparable roles in their community than with people of different hierarchical levels. Similarities in bonding and linking in CB-villages may result from CBNRM policies, which provide charcoal producers with power in decision making and possibilities for information exchange with people of different socio-economic status (Aldrich 2011, Marín *et al* 2012, Tavits 2006), presenting producers with new ideas and values (Woolcock 2001). In fact, anecdotal information suggests that charcoal producers in CB-villages welcome more interactions, as several producers indicated that charcoal producer association membership provided them with opportunities to generate or increase their income, and allows for collaboration and knowledge sharing. Given the benefits of associations, we were surprised that charcoal producers in OA-villages do not self-organize to create them; yet this may be explained by the informality or illegality of charcoal production in OA-villages (Schure *et al* 2013), and a general individuality found in prior studies (Baumert *et al* 2016, Butz 2013).

### 4.2 Formality and quality of interactions

#### *4.2.1Formality of interactions*

We find that charcoal producers have higher membership to charcoal producer associations in CB-villages. This is not surprising as membership of charcoal producer associations is obligatory in CB-villages to legally produce charcoal. Additionally, enhanced benefits from association membership mentioned by producers are in line with a recent studies on charcoal production systems (Kamwilu *et al* 2021) and studies on the social-economic benefits of cooperatives in honey, fishery and agricultural systems (Johnson and Van Densen 2007, Maas *et al* 2014, Serra and Davidson 2021). Besides the stated benefits of charcoal producer associations, this process may exclude outsiders and reduce innovation, leading to conformity of thinking (Maas *et al* 2014). Although evidence suggests that group formation could potentially result in exclusion of new participants (Oostdijk *et al* 2019), we find no evidence that trainings excluded people from participating in CBNRM. Several charcoal producers even mentioned that anyone can produce charcoal under CBNRM and that no exclusion takes place.

The lack of or limited formalization of charcoal production through associations may explain low bonding in OA-villages (the charcoal producer association one producer in OA2 indicated to be member of was situated in another village). Interestingly, several charcoal producers in OA-villages have joined other associations, indicating general awareness of their existence, concept and the benefits that may be derived from them. As collectivism, committees, associations, cooperatives and training sessions may lead to more trust between people (Maas *et al* 2014), introducing them may enhance cooperation among charcoal producers in OA-villages. Additionally, they may empower marginalized groups, such as female charcoal producers (Ihalainen *et al* 2020), to enter the market, as observed for female actors in agricultural systems (Ferguson and Kepe 2011, Tesfay and Tadele 2013). Because associations are considered an integral part of local Tanzanian development processes (United Republic of Tanzania, 1982), they may be implemented without the involvement of third parties. This may provide Tanzanian charcoal producers with advantages over charcoal producers in other countries, as legal feasibility of cooperatives and associations determines their implementation and success (Wielgus *et al* 2014).

#### *4.2.2 Quality of interactions*

We found comparable reported feelings of support by other villagers and Village Council members in both CB-villages and OA-villages. This counters the hypothesis that CBNRM enhances support, and indicates that despite many interactions in CB-villages, these do not increase feelings of support. This could be because feelings of support were already high in both village types, related to the well-established decentralized governance system of Tanzania in accordance with Tanzania's Local Government Act (1982) (Blomley, 2006; United Republic of Tanzania, 1982). The Tanzania Local Government Act of 1982 dictates that interactions with villagers by District Councils and TFS ought to be indirect through village representation by Village Council members and village level District staff in the Ward Development Committee  United Republic of Tanzania, 1982). For this reason, District governments may fail to function as a bridge between local formal and informal actors and national scale governance agencies, which may challenge effective governance of charcoal production (van 't Veen *et al* 2022). Despite their indirect relation to the District Council and TFS, several charcoal producers indicated that they feel supported by them because they take care of forests and interact with their Village Council. This suggests a general understanding of the value of decentralized governance through multiple governance agencies with varying tasks by charcoal producers, despite the experienced lack of direct interaction.

Although we observe that charcoal producers of CB-villages on average interact with more producers than those of OA-villages, these interactions are not as frequent. This may related to sporadic meetings of producer associations which may nevertheless be efficient, as they include many producers. Theory suggests that sporadic interactions provide more non-redundant information, which complements redundant information that is exchanged through more regular interactions (Levin and Cross 2004). Nevertheless, sporadic interactions may produce lower community resilience because the risk of a loss of a connection is larger for sporadic than frequent interactions (Levin and Cross 2004). For example, if charcoal producer associations are abolished, sporadic interactions between charcoal producers may cease to exist. Hence, we recommend active effort to continue facilitation of both frequent and sporadic interactions between charcoal producers in CB-villages. The multiple benefits of charcoal producer associations mentioned by charcoal producers, as well as their wish to continue them, indicates that they are currently willing to participate in them. Willingness of members to participate in cooperatives is the most important proxy of active participation (Verhees *et al* 2015), which is influenced by external factors, such as education, operational costs (Zheng *et al* 2012), and household characteristics (Mojo *et al* 2017).

One of the major challenges for sustainability transitions in the energy sector (and other sectors) is discontinuation and upscaling (Johnstone and Newell 2018, Mills *et al* 2019). Our finding that charcoal production under CBNRM creates denser and more decentralized social networks, suggests that the CBNRM approach implemented under the TTCS project has strong potential to initiated sustainability transitions in charcoal production systems, if scaled up. To achieve this, charcoal production under CBNRM should function independently from third parties. Unfortunately, we find indications that specific attributes of the TTCS project are being discontinued just two years following the departure of TFCG. For instance, charcoal producers from CB-villages felt that charcoal producer associations are being discontinued, that they are no longer a member, or that association members do not meet anymore. Several charcoal producers are concerned and would like their Village Council to re-instate or maintain their association. This abolishment of charcoal producer associations may result from a lack of experience in the management and leadership of associations in CB-villages, as this requires specific knowledge and skills, such as communication with multiple stakeholders, resource allocation, and technical operational skills (Cook 1994). Active facilitation charcoal producer association management trainings may enable access to necessary knowledge and skills to manage associations to assure continuation of charcoal producer associations.

Charcoal producers in CB-villages also expressed that they experienced an up to 50% revenue drop per charcoal bag (50 kg) in the last 5 years. This price drop is likely a consequence of the revenue-sharing scheme implemented under CBNRM, where part of the price charcoal buyers pay per bag is retrieved by the Village Council as tax that is invested in forest management and community development projects that benefit both charcoal producers individually and the communities they are part of (Lund and Treue 2008, Mustalahti and Lund 2010). Many interviewed charcoal producers in CB-villages indicated that they produced less or even abandoned charcoal production in response revenue drop because they were unable to sustain their livelihoods. Hence, it is likely that a loss of income and, therefore, market participation may partially explain the discontinuation of specific aspects of TTCS participatory forestry scheme, which may have social-economic consequences for entire villages. This drop in revenue contrasts with literature that finds increases in revenue upon engagement in cooperatives (Serra and Davidson 2021) but is in line with literature that shows competition between illegal and legal forest products, where buyers prefer to buy cheaper illegal products over legal ones under limited enforcement (Ameha *et al* 2014, Mohammed and Inoue 2012a, Richards *et al* 2003).

### 4.3 Equality in charcoal producer networks

Our selection of interviewees based on wealth status corroborates that charcoal production is indeed mainly an activity of the poor and poorest (Khundi *et al* 2011, Vollmer *et al* 2017). However, unlike previous studies (Vyamana 2009, Ellis and Freeman 2004, Ellis and Mdoe 2003), we found no differences in per-node metrics between poor and poorest wealth classes. This lack of differences might relate to dedicated efforts of TFCG and Village Councils to include members of the poorest wealth category in charcoal producer associations of CB-villages, as shown by the slightly higher proportion of poorest producers involved in charcoal producer associations compared to poor producers. This may also explain why poorest charcoal producers report high levels of support by other villagers and the Village Council. Nevertheless, caution should be taken when interpreting these results, as splitting our sample into wealth categories reduced the power of our statistical analyses. Despite the rarity of non-poor producers, they may still play an important role, as observed for one OA-village, where we found that one non-poor producer connected multiple producers together.

### 4.4 Lessons learned

Despite our interesting findings, some caution is warranted to interpret them. The survey used in this study was relatively long, focusing more broadly on livelihoods of which social networks were only one component. The interviews took two-hours, which may have affected the concentration of the interviewees and their willingness to explain their answers (Burchell and Marsh 1992). In addition, we found initial hesitation of charcoal producers in OA-villages to engage in interviews, which we attributed to informality or illegality of charcoal production. However, after a first round of interviews more charcoal producers expressed their wish to be interviewed, likely because the surveys did not contain (many) questions that caused distrust, even though some may still have refrained from answering certain questions completely or truthfully. Covid-19 progression and limited awareness of those who produce charcoal by the Village Council reduced the number of charcoal producers interviewed in OA-villages. Our sampling also suffered from delays due to misunderstandings by village leaders about sampling procedures, inabilities of village leaders to inform interviewees prior the start of the interviews and long traveling times on difficult terrain to interviewees, which caused some producers to provide less detailed answers because of late hours. Questions on interactions required interviewees to recall names, which was at times challenging because not all charcoal producers could remember last names or only remembered nicknames. In case a nickname and a full name was provided by the interviewee, both names were written down. These two names enabled the identification of the full name of a nicknamed person in most occasions. In case only a first name or nickname was written down and could not be linked to a full name provided by another interviewee, this person was included as a separate node in the network. This could have resulted in an overestimation in the number of nodes in the network, and may have influenced its structure and characteristics. Nevertheless, the bootstrap results indicate that the social networks (both bonding and linking) are relatively robust to edge swapping and node removal, with relatively low variation in network diameter, distance and reciprocity (Fig. 4), despite the fewer charcoal producer interviewees in open access villages. Hence, we are confident that we robustly compare charcoal producer networks of OA-villages and CB-villages. We largely avoided effects of other third party projects by selecting those study villages that had no prior project in place concerning forest use or protection through consultation with TFCG and the District Council of Kilosa prior to our fieldwork. However, we could not disclose impacts of local circumstances on social network structures.

## 5. Conclusions

Our study shows that governance transitions in social-ecological systems may modify the density, intensity and heterogeneity of interactions in a social network between people with comparable roles and across hierarchical levels. We demonstrate this empirically for two distinct governance types in charcoal production systems: open access and CBNRM. Our analysis of 160 surveys highlights that bonding and to a certain extent linking in charcoal producer networks is denser in CBNRM than in open access. We attribute these network characteristics to formalization of interactions between charcoal producers through associations, training schemes and harvesting protocols, and the interactions with their Village Council established under CBNRM. These results corroborate that implementing interventions that enable formal communal organization can successfully densify and decentralize social networks, and promote network heterogeneity, important for effective participatory management of shared natural resources. The main challenge remains continuation and upscaling of formal participatory forestry schemes upon departure of a third party. Future research could focus identifying ways in which externally fostered formal activities and associations can be transferred and maintained. For instance, whether more intensive integration of higher governance levels could help establish formal communal organization, or whether self-organization of charcoal producers could be fostered through charcoal producer associations. Finally, it is important to identify the contribution of specific policy attributes to bonding and linking in charcoal producer networks, e.g., whether network characteristics can be attributed to the formation of charcoal producer associations, forest management practices, training sessions or a combination of policies. Future research may further assess whether densification and decentralization of social networks upon transitions to CBNRM contributes to more sustainable charcoal production by balancing conservation and exploitation of shared natural resources and the fulfillment of environmental and social-economic goals of CBNRM initiatives.

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**Data Availability:**
Anonymized survey data is available upon request.

## Author contributions

The author contributions are based on CRediT (Contributor Roles Taxonomy), which aims to recognize individual author contributions to facilitate collaborations and to diminish disputes among authors (https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement).

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# Chapter 7

## Effects of forest governance on synergies and trade-offs in charcoal producer livelihoods

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*This chapter is submitted to the journal Energy for Sustainable Development*

**Chapter 5** and **Chapter 6** provide insights into specific livelihood capitals of charcoal producers under different governance systems, namely (i) natural capital (i.e., forest use in resource systems) and (ii) social capital (i.e., charcoal producer networks of users). Although prior knowledge is available on importance of charcoal production to derive financial capital (i.e., income) and human capital (i.e., education), the relationships between the different capitals and their influence on charcoal production remains unclear.

In **Chapter 7**, I use data of 160 livelihood surveys spread over six study villages to assess synergies and trade-offs between different livelihood capitals under two different charcoal production systems: (i) open access and (ii) communal management systems. With this study, I aim to increase our understanding of charcoal producers as users of charcoal production systems. I also aim to fill important knowledge gaps on interactions between different livelihood capitals and reflect on the results of **Chapter 3**, **Chapter 5** and **Chapter 6** of this study.

**Figure 7.1** provides an overview of the social-ecological system components assessed in **Chapter 7**, their interactions, and the specific charcoal production systems compared. The **Supplementary Materials** of **Chapter 7** can be found in the **Appendix of Chapter 7** of this thesis.

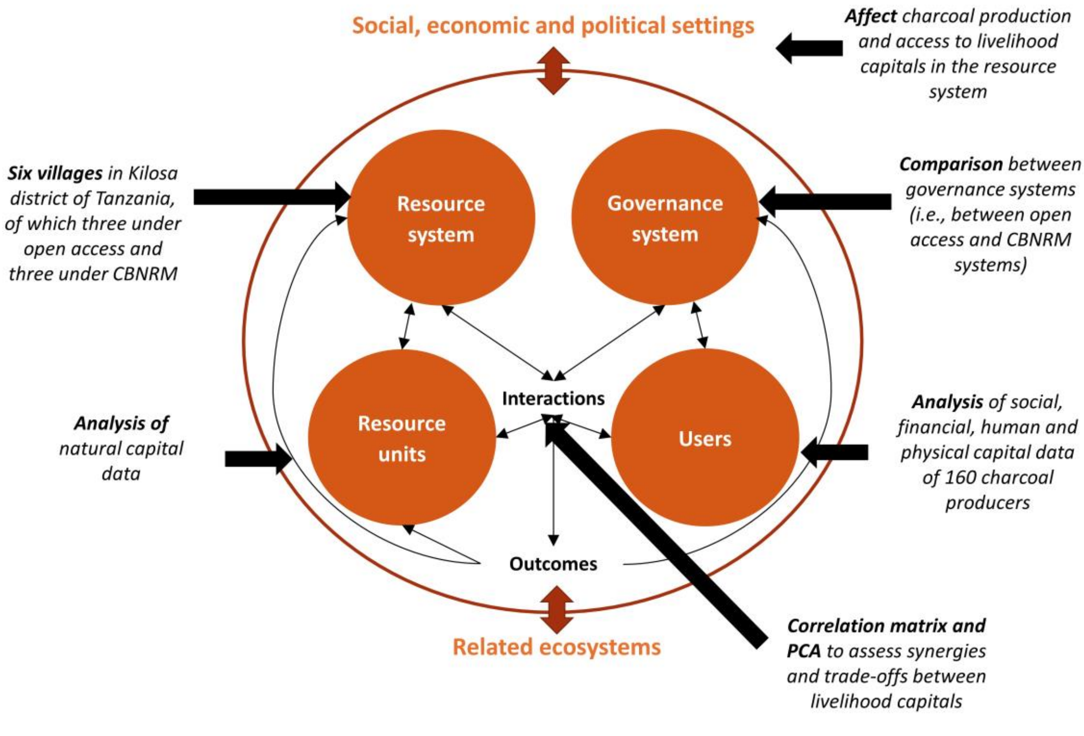

**Figure 7.1.** The social-ecological system components assessed in **Chapter 7**, their interactions, and the specific charcoal production systems compared. CBNRM = community-based natural resources management.

**Submitted scientific paper**

# Effects of forest governance on synergies and trade-offs in charcoal producer livelihoods

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## Abstract

The Sustainable Development Agenda for 2030 recognizes the need to integrate Sustainable Development Goals to reduce both poverty and environmental pressures. Biomass-based renewable energy systems, such as charcoal production systems, face trade-offs between socio-economic benefits and forest sustainability. In the case of charcoal production systems, this trade-off results in 7% of deforestation globally, while fostering energy, income and other socio-economic benefits to hundreds of millions of people. In this paper, we assessed governance effects on charcoal producer livelihoods through a statistical comparison of access to and trade-offs and synergies between five livelihood capitals in three villages under open access and three villages under community-based natural resources management (CBNRM) in Kilosa district Tanzania, based on 160 surveys, which informed 19 indicators derived from 41 survey questions. In line with its aims, we show that CBNRM significantly enhances charcoal producers access to aspects of natural, social and partially human capital, including perceived forest sustainability, interactions between charcoal producers, and technical knowledge. This results in a trade-off between financial capital, in the form of income per charcoal bag, and other capitals because part of this income is shared through a locally managed revenue-sharing scheme, which invests in forest management and community development projects that provide livelihood benefits to both individual charcoal producers and whole communities. We find that livelihood capitals are not singular because indicators of the same capital exhibit synergies and trade-offs and because villages under the same governance regime show different synergies and trade-offs between livelihood capital indicators, indicating that besides governance other social-ecological factors play a role in shaping livelihoods. We conclude that there is a need for more holistic multidimensional analyses of trade-offs and synergies in livelihoods to understand their response to forest governance and each other to further improve current governance regimes and assure their adaptation to local circumstances.

## Highlights

- We use the sustainable livelihood approach to study livelihood access, synergies and trade-offs.
- We assess 160 charcoal producer livelihoods in three open access and three CBNRM villages.
- We find higher access to natural, social and partly to human capital under CBNRM than open access
- We find trade-offs between financial and other capitals resulting from revenue-sharing schemes.
- Same-capital indicators exhibit synergies and trade-offs; hence livelihood capitals are not singular.

## 1. Introduction

The Agenda 2030 for Sustainable Development (UN 2021) recognizes that about 1.6 billion people around the world depend on forest resources to pursue their livelihoods, which mitigates poverty and hunger (Angelsen *et al* 2014). Yet, after decades of research and policy interventions, it still proves challenging to harmonize rates of forest growth and use (Venter *et al* 2016, Wackernagel *et al* 2021) and persistent trade-offs remain between those Sustainable Development Goals that aspire greater human welfare and those aspiring sustainable environmental management (Nerini *et al* 2018). This challenge is also found in energy systems relying on biomass-based renewable energy, such as charcoal production systems (Alfaro and Jones 2018). Secure access to biomass-based renewable energies is vital in the tropics, in particular in Sub-Saharan Africa, because of low or insecure access to alternative energies, such as gas (Ejigu 2008, Lusambo 2016), and the role of biomass-based renewable energy production as a livelihood diversification strategy (Jones *et al* 2016, Smith *et al* 2017). Charcoal production systems are mainly governed under open access, defined as those governance systems where charcoal producers limitedly adhere to laws, rules and regulations (van 't Veen *et al* 2021). While, charcoal production provides income to 40 million people in the charcoal producer value chain and vital energy to hundreds of millions of people (FAO 2017), it also causes up to 7% of deforestation, as well as forest degradation (Chidumayo and Gumbo 2013), in particular as a by-product of agriculture (Iiyama *et al* 2017). Since numbers of people relying on charcoal to fulfill their livelihoods are only expected to grow, leading to a 5% increase in demand by 2100, charcoal-related forest loss and degradation will likely continue or increase (Santos *et al* 2017, IEA 2014, Hillring 2006). This may ultimately jeopardize the sustainability charcoal producer livelihoods (Brouwer and Magane 1999, Schaafsma *et al* 2014, Woollen *et al* 2016), potentially increasing poverty (Schure *et al* 2014, Vollmer *et al* 2017). Therefore, it is vital for scientists and policy makers to identify ways in which forests and livelihoods can be reconciled in charcoal production systems (van 't Veen *et al* 2021).

Currently, governance transitions from open access to alternative forest governance systems (i.e., system through which forest use is directed and controlled) are being promulgated to mitigate charcoal-related deforestation and forest degradation and/or to sustain livelihoods (FAO 2017). Upon a governance transition, new laws, rules and regulations are implemented in a specific area (e.g., a village) to govern forest use for charcoal production (Kamwilu *et al* 2021), e.g., by devolving power to local communities or individuals (Zulu 2010), and/or by implementing a specific forest harvesting plan that dictates forest management (Ishengoma *et al* 2016). Over the past decades, good governance principles have been identified, such as locally generated rules and participation in decision making, which have been linked to both sustainable forest use and sustainable livelihoods, defined as vital resources to sustain livelihoods (Newton *et al* 2016, Persha *et al* 2011). An example of a governance regime based on good governance principles that is introduced in charcoal production systems is community-based natural resources management (CBNRM) (Ishengoma *et al* 2016, WB 2010b). Generally, CBNRM of forest resources aims to mitigate both forest degradation and maintain and/or improve livelihoods by providing continuous access to forest resources, knowledge, social networks and income through a revenue-sharing system (Gruber 2010). Under CBNRM, forest users, who financially benefit from the use and sale of forest products, put a share of their income in the form of a tax on forest products into a community fund through a revenue-sharing system (Lund 2007, Mustalahti and Lund 2010). The revenues collected in this community fund are invested in the forest management (e.g., in forest patrols, training schemes, associations in which shared decisions are made, and supervision of forest harvesting activities) or in community development (e.g. water supply and health insurance for all community members) (Lund 2007, Mustalahti and Lund 2010). Hence, CBNRM sustains itself over time through this revenue-sharing scheme, and not only provides socio-economic benefits to individual forest users but also to the entire community of which forest users are part.

Although promising, the introduction of good governance principles does not always result in sustainable forest use and livelihoods (Newton *et al* 2016, Persha *et al* 2011). Sometimes the effect is even reverse (Newton *et al* 2016, Persha *et al* 2011), resulting in a mismatch between governance goals and reality (Dressler *et al* 2010). Such mismatch may lead to discontentment regarding livelihood benefits by local communities, potentially causing them to disobey rules and regulations (Blaikie 2006), which may result in continued environmental degradation (Ranjan 2018). Despite the diversity of outcomes, policy makers continue to base decisions on preexisting assumptions about good governance (McShane *et al* 2011). Therefore, it is important to conduct impact assessments to better understand effects of forest governance systems based on good governance principles on forests and livelihoods, to further improve them in order to prevent mismatches between governance goals and reality in the future. For instance, we may learn from case studies that show enhanced livelihood benefits and/or forest resources through forest governance (Blomley *et al* 2008, Lund 2007, Gobeze *et al* 2009) and compare them with case studies that identify contrasting livelihood and forest outcomes induced by similar initiatives (Ameha *et al* 2014). It is particularly important to carry out such impact assessment in charcoal production systems because limited attention is paid to sustainable charcoal production as a policy option in the tropics (Doggart and Meshack 2017, Branch *et al* 2022, Mabele 2020). Besides this, current forest laws, rules and regulations often do not concern charcoal production directly but integrate it as one of the forest uses (van ’t Veen *et al* 2022), even though charcoal value chains differ substantially from those of other forest products, such as timber or fuelwood (FAO 2017). Finally, forest laws and policies often unjustifiably mention charcoal as a product that causes environmental destruction and should, therefore, be prohibited (Branch *et al* 2022, Mabele 2020).

The main reason for mismatches between governance goals and reality is complexity in livelihoods (Agrawal 2007). In order to foster sustainable livelihoods in charcoal production systems, charcoal producers need access to a range of livelihood resources, also called capitals, including (i) forest biomass used to produce charcoal (natural capital), (ii) knowledge about charcoal production and health (human capital), (iii) cooperation in forest management (social capital), (iv) income and savings derived from charcoal (financial capital), and (v) infrastructure (physical capital) (Scoones 1998). To foster access to all livelihood capitals, they should positively influence each other (i.e., synergize) (Biggs *et al* 2015, Orchard *et al* 2020). Yet, in reality trade-offs often occur between them (Kibria *et al* 2018, Zaibet *et al* 2011). Examples of synergies between livelihood capitals are enhanced knowledge exchange upon dense social networks (Díez-Vial and Montoro-Sánchez 2014) and higher income with access to tree species that produce high quality charcoal (Nabukalu and Gieré 2019). Examples of trade-offs between livelihood capitals are increased income with a loss of forest resources (Steffan-Dewenter *et al* 2007), mainly in areas where illegal forest use takes place (Appiah *et al* 2021, Sommerville *et al* 2010), or forest loss due to an increase in the quality of infrastructure under unregulated production (Barber *et al* 2014). Interestingly, trade-offs can turn into synergies and vice versa; for example both sustainable livelihoods and forest use may be fostered upon changes in forest governance that devolve power to local communities (Chhatre and Agrawal 2009). Finally, access to and synergies and trade-offs between livelihood capitals, such as income and skills may vary between producers of different genders because female charcoal producers often have lower access to forest resources, income, social networks and time than their male counterparts (Ihalainen *et al* 2020). The same accounts for wealth status (Vyamana 2009) because charcoal producers in non-poor wealth classes have more assets than those in poorest wealth classes (Vollmer *et al* 2017). It is important to find dominant patterns and causal pathways for synergies and trade-offs between livelihoods because this allows for adjustments to current governance regimes to provide better livelihood outcomes, while mitigating forest degradation and deforestation (Persha *et al* 2011).

In this study, we aim to understand effects of governance on trade-offs and synergies in charcoal producer livelihoods. We specifically focus on two extremes of forest governance through a case study in Kilosa District, Tanzania that compares charcoal producer livelihood capitals, their synergies and trade-offs under open access with those under CBNRM. Comparing these two governance regimes informs us about the potential social-ecological effects of forest governance transitions. We hypothesize that charcoal producers have higher and sustainable access to livelihoods capitals under CBNRM than under open access as a result of revenue-sharing (Fig. 1). More specifically, we expect that the revenue-sharing scheme allows communities to invest in forest management, which fosters sustainable forest use, training on sustainable charcoal production and shared decision-making schemes; thus enhancing natural capital, human capital and social capital. Besides this, we expect that community investments in infrastructure and health insurance enhance access to physical capital on the community level and human capital at the individual level. Because part of the collected taxes are paid to regional and national governments, who in turn provide human capital in the form of manpower to monitor forests, we expect increased natural capital. As a consequence, we expect that the financial capital individual charcoal producers obtain from charcoal production reduces. In open access systems, we expect that charcoal producers keep most of the income they derive from charcoal production, and only lose some as a consequence of fines for illegal production. Hence, we expect higher financial capital of individual charcoal producers under open access than CBNRM. However, because charcoal buyers often accept informal bribes, rarely pay taxes under open access, and the

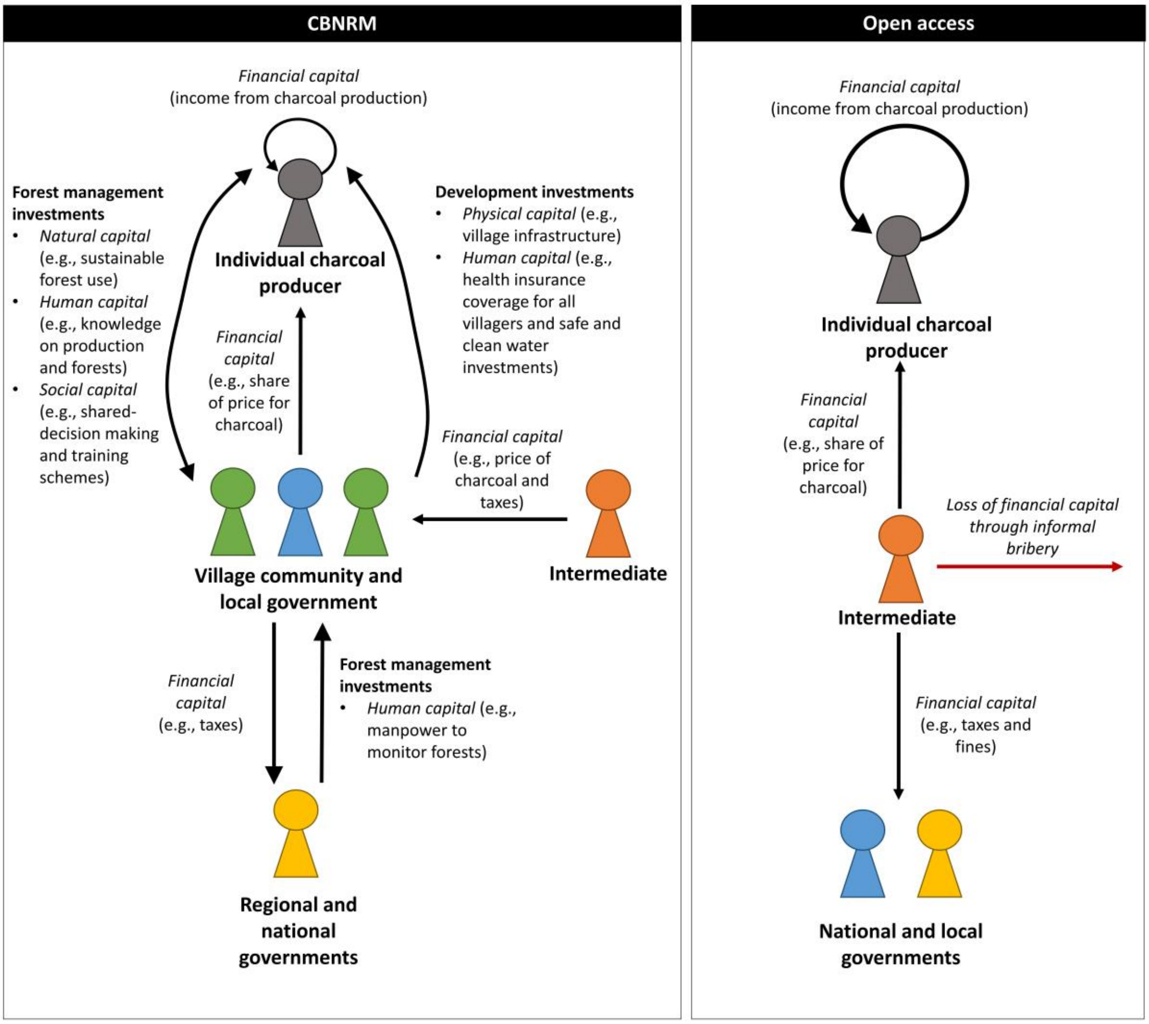


**Figure 1.** Conceptual framework providing an overview of expected flows of livelihood capitals under two different governance regimes for our case study in Kilosa District, Tanzania. CBNRM = community-based natural resources management. Intermediates are buyers of charcoal bags, who transport them to centers of demand, such as cities.

collected taxes do not stay in the community, we expect that the governance regime does not actively transform financial capital of charcoal producers into other livelihood capitals, does not mitigate deforestation and forest degradation, and does not directly benefit the community they are part of. Therefore, we hypothesize that charcoal producers operating under open access have lower social, human and natural capital than those operating under CBNRM. We hypothesize higher physical capital of charcoal producers under open access than CBNRM because we expect charcoal producers to invest their financial capital in physical capital. Finally, we expect that poorest charcoal producers have lower access to livelihood capitals because they have less entitlements and depend on relatively more precarious livelihoods. We also hypothesize that female charcoal producers have lower access to livelihood capitals than their male counterparts due to unfavorable gender relations that determine access and control over forest resources.

## 2. Methodology

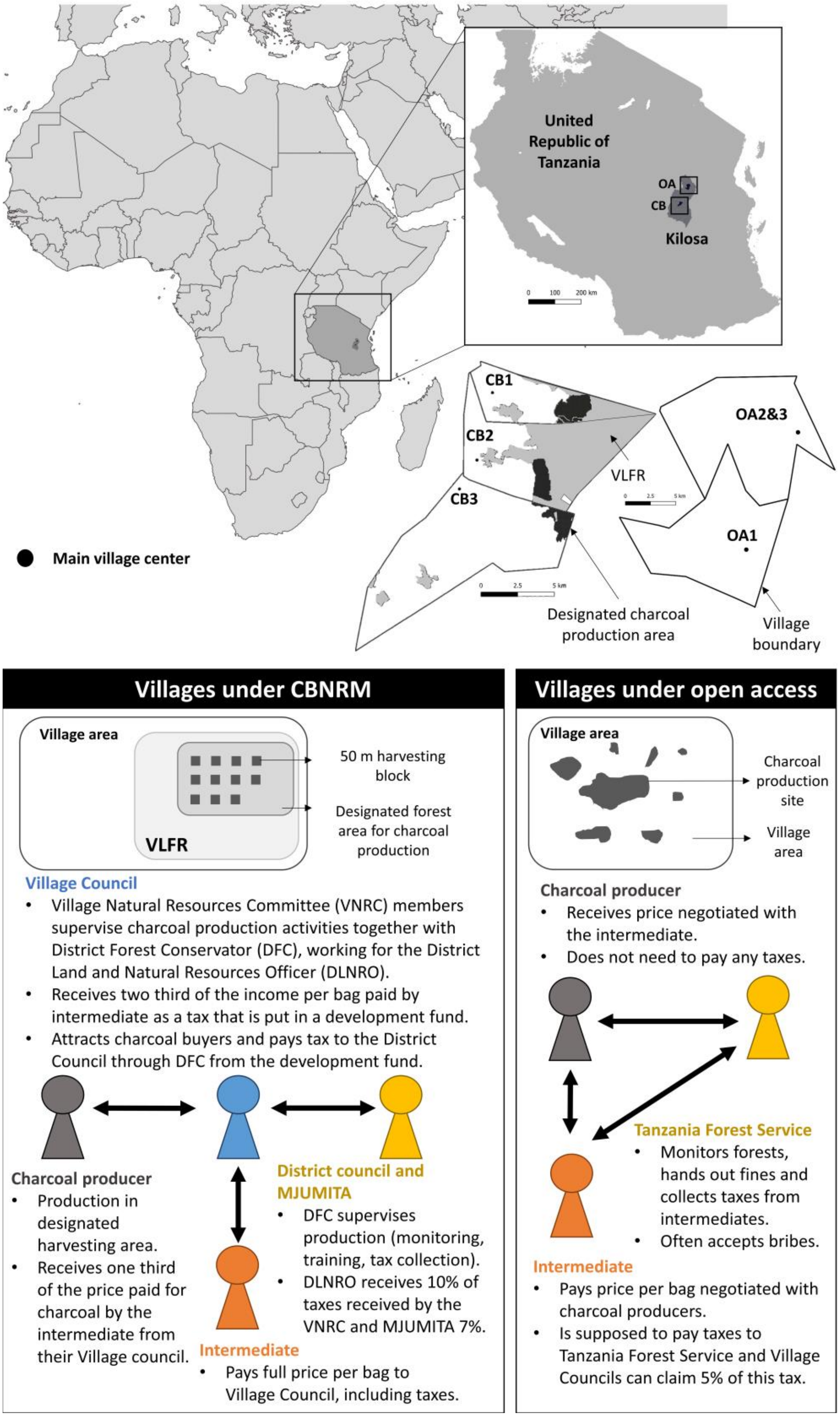
We conducted a counterfactual analysis (i.e., analysis during which outcomes of policy interventions are compared to a business as usual scenario) by comparing the outcomes of one business as usual governance regime (i.e., open access) to an intervention that introduced a forest governance regime that aims to promote sustainable livelihoods, while mitigating forest utilization pressure from charcoal and other forest uses (i.e., CBNRM). This analysis informed us about the potential livelihood implications of governance transitions in charcoal production systems.

### *2.1 Study area*

The fieldwork for our study was conducted in Kilosa district of Tanzania, approximately 300 km west of Dar es Salaam city (Fig. 2). Wood fuel supplies energy to about 92% of the Tanzanian population, specifically in the form of charcoal in urban areas (Sheya and Mushi 2000). Approximately 33% of deforestation in Tanzania is attributed to charcoal production (Doggart and Meshack 2017), and part of it is due to charcoal production as a by-product of the conversion of forest land into agriculture (Iiyama *et al* 2017). Kilosa District mainly includes Miombo woodlands (Ishengoma *et al* 2016). The temperature ranges between 19 and 20 °C with an average of 25 °C, elevation ranges between 400 and 2200 m above sea level and precipitation ranges between 800 and 1200 mm per year (Ishengoma *et al* 2016). Rainfall is bi-modal, i.e., long season between March and May and short season between November and January (Ishengoma *et al* 2016).

Tanzanian forests are managed by multiple government agencies, namely by Village Councils at local scale, Wards and District governments at regional scale, and Tanzania Forest Service (TFS) at national scale (Doggart 2016). In order to receive permission for legal commercial forest use on village land, Village Councils have to apply for formal permits to produce commercial charcoal, timber and other forest products, and these products should be produced within a designated forest area, called a Unreserved Forest on Village Land, in a defined Village Land Forest Reserve (VLFR) within a village boundary (Lund 2007, Mabele 2020, Mustalahti and Lund 2010). The Village Council also designs a sustainable forest harvesting plan for the VLFR, to be approved by a District Harvesting Committee, which includes members of the Village Council and District Council (Lund 2007, Mabele 2020, Mustalahti and Lund 2010). Once all legal requirements are fulfilled, a special committee within the Village Council, called the Village Natural Resources Committee (VNRC), may issue permission to individual or groups of charcoal producers to harvest forest within the designated area for charcoal production, as specified in the sustainable forest harvesting plan (Lund 2007, Mabele 2020, Mustalahti and Lund 2010). The charcoal is sold to intermediates (e.g., transporters and/or wholesalers, also called dealers or buyers) (Ishengoma *et al* 2016). Intermediates are attracted by Village Councils and officially registered by the District Forest Conservator, who works under the District Land and Natural Resources Officer (DLNRO) (Lund 2007, Mabele 2020, Mustalahti and Lund 2010). Intermediates make deals about the number of charcoal bags they buy from Village Councils, as well as the amount they pay for them (Lund 2007, Mabele 2020, Mustalahti and Lund 2010). Hereafter, charcoal producers produce charcoal, and receive their share of the revenues from the Village Council (Lund 2007, Mabele 2020, Mustalahti and Lund 2010), which currently totals approximately one third of the total price by the intermediate (personal communication Vincent Gerald Vyamana, 2022) and is documented in village-specific by-laws (Ishengoma *et al* 2016). The other two thirds are kept by the VNRC as tax, which is put in a community fund, used to invest in community development projects (e.g., water supply and health insurance for all community members), as well as forest management (e.g., in forest patrols and supervision of forest harvesting activities) (Lund 2007, Mabele 2020, Mustalahti and Lund 2010). The height of the tax collected by the VNRC is specified in by-laws (Lund 2007, Mabele 2020, Mustalahti and Lund 2010). The village council pays 10% of the tax to the District Council, which is collected by the DLNRO (Government of Tanzania 2019) (confirmed through personal communication with Vincent Gerald Vyamana, 2022). Under Government Notion (GN) 417, the taxes are no longer forwarded to the nationally operating TFS (Government of Tanzania 2019). Instead, TFS directly claims 5% of the taxes from the intermediates in a separate transaction (Government of Tanzania 2019) (confirmed through personal communication with Vincent Gerald Vyamana, 2022). Forests are monitored by both the VNRC and the District Forest Conservator, among others through patrols (Lund 2007, Mabele 2020, Mustalahti and Lund 2010).

In total, we studied in six villages within Kilosa District, which were selected because of their distinct governance regimes (Fig. 2). Three villages participate in the CBNRM project Transforming Tanzania's Charcoal Sector (TTCS) of the Tanzania Forest Conservation Group (TFCG). From here on we refer to these villages as CB-villages. The other three villages do not participate in this CBNRM project and no VLFR exists in these villages; thus charcoal production occurs under open access (i.e., without formal regulations on who accesses and uses the village forest for charcoal production). From here on, we refer to these villages as OA-villages. In the three CB-villages, the TTCS project aims to mitigate deforestation and forest degradation, and to support local livelihoods (Ishengoma *et al* 2016). The



**Villages under CBNRM**

**Village Council**
- Village Natural Resources Committee (VNRC) members supervise charcoal production activities together with District Forest Conservator (DFC), working for the District Land and Natural Resources Officer (DLNRO).
- Receives two third of the income per bag paid by intermediate as a tax that is put in a development fund.
- Attracts charcoal buyers and pays tax to the District Council through DFC from the development fund.

**Charcoal producer**
- Production in designated harvesting area.
- Receives one third of the price paid for charcoal by the intermediate from their Village council.

**District council and MJUMITA**
- DFC supervises production (monitoring, training, tax collection).
- DLNRO receives 10% of taxes received by the VNRC and MJUMITA 7%.

**Intermediate**
- Pays full price per bag to Village Council, including taxes.

**Villages under open access**

**Charcoal producer**
- Receives price negotiated with the intermediate.
- Does not need to pay any taxes.

**Tanzania Forest Service**
- Monitors forests, hands out fines and collects taxes from intermediates.
- Often accepts bribes.

**Intermediate**
- Pays price per bag negotiated with charcoal producers.
- Is supposed to pay taxes to Tanzania Forest Service and Village Councils can claim 5% of this tax.

**Figure 2.** Study area overview and a visualization of forest use and the interactions between actors under CBNRM and open access. CBNRM = community-based natural resources management. VLFR = Village Land Forest Reserve.

TTCS project was initiated in collaboration with the District Council of Kilosa and fits to the Community Based Forest Management Guidelines (Ministry of Natural Resources and Tourism, 2007). The application for the VLFRs was officially approved in the year 2014 in CB-villages (Ishengoma *et al* 2016). The harvesting plan dictates that harvest should follow a 24 year harvesting cycle in a checkerboard scheme (50 x 50 m blocks) (Ishengoma *et al* 2016). The blocks are located at least 60 m from water bodies and only non-timber tree species with a diameter at breast height larger than 15 cm can be harvested (Ishengoma *et al* 2016). Further, charcoal producer associations were introduced (Ishengoma *et al* 2016). Charcoal producers are required to be a member of this association to legally produce charcoal, to apply for the right to produce charcoal in the harvesting blocks, and to receive a training on sustainable charcoal production (Ishengoma *et al* 2016). Villages under TTCS project pay an additional 7% of the taxes they receive from charcoal production to MJUMITA, a forest conservation network in Tanzania (https://mjumita.or.tz/, last accessed on the 30th of March 2022), to cover costs for technical support (Ishengoma *et al* 2016). In the OA-villages, charcoal producers produce charcoal in an unregulated fashion from the forest resources in their village; hence production is illegal. In these villages, the intermediate is responsible for paying taxes to the nationally operating Tanzania Forest Service (Doggart 2016). The village government has the right to claim up to 5% of the tax charged to buyers but in practice this tax is rarely claimed (personal communication Vincent Gerald Vyamana, 2022). Besides this, taxes are usually not paid in full by intermediates or are avoided altogether and informal bribery is common (Mustalahti and Lund 2010). Hence, in CB-villages more taxes from forest produces are collected by the communities than in OA-villages, theoretically allowing for higher direct investments in forest management and community development. The OA-villages are located approximately 30 km north of Kilosa city, while the CB-villages are located approximately 20 km south of Kilosa city. Because of the distance between the two village types, limited or no direct communication and commodity exchange occurs between the charcoal producers in the villages. Some communication between Village Council members of the two village types may occur during assemblies. However, we expect that large distance between the village types will generally reduce the influence villages have on each other. Thus, we assume that CB-villages and OA-villages are independent samples, which can be statistically compared with each other and, therefore, can be considered counterfactuals.

In this study, we refer to the TTCS project as a CBNRM project, the umbrella term for natural resources management, which indicates a devolution of land tenure rights to local communities and active communal participation and decision-making (Dressler *et al* 2010). We decided not to use forest system-specific derivatives of CBNRM, such as community-based forest management (CBFM), participatory forest management (PFM) (Friedman *et al* 2020), or joint forest management (JFM) (Blomley 2006). This, because the preferred term to communicate about CBNRM of forest resources differs between countries and multiple terms are used interchangeably. Additionally, the use of the term CBNRM positions our study in the wider context of CBNRM, which is useful because our results may be informative for other CBNRM schemes and other governance regimes based on similar objectives and principles.

### *2.2 Data collection*

#### *2.2.1 Data collection approach*

We conducted a livelihood analysis based on the Sustainable Livelihoods Approach (SLA), which is a method based around the central idea that people, in particular people in rural contexts, need access to a range of livelihood resources in order to foster sustainable livelihoods (Scoones 1998). In the original Working Paper in which the SLA was introduced, Scoones (1998) categorized livelihood resources into groups, which he refers to as capitals. This categorization allows for a comparison between livelihood resources and an assessment of their relationships. The SLA is a useful tool to better understand implications of governance on livelihoods because access to livelihood capitals is influenced by formal governance (i.e., ways in which governing bodies, such as local and regional governments interact with each other to negotiate, make and enforce decisions regarding forest use and conservation) and informal governance (i.e., societal norms) (Scoones 1998). In this study, we focused on formal governance but acknowledge that informal governance can influence livelihoods in parallel and may affect the success of formal governance regimes (Ashu 2016, Osei-Tutu *et al* 2015, Pacheco *et al* 2008). We assessed livelihood capitals charcoal producers obtain individually, rather than those obtained at a community level because we were interested in the impacts of governance transitions on individual charcoal producers and because we did not have the means to assess livelihoods in a sufficient number of villages to allow for a statistical comparison between livelihood capitals at community level. We strongly recommend further studies on synergies and trade-offs between livelihood capitals at community scale, e.g., similar to the study of Lund (2007) by comparing forest management and community development between a number of villages under CBNRM and open access that allows for statistical comparison.

The primary data used in this study was information on indicators of five livelihood capitals, namely financial capital, human capital, social capital, natural capital and physical capital (see Table 1 for a rationale for their inclusion). We decided to assess these capitals because they are vital for charcoal producers to sustain their livelihoods and because we expected effects of governance on these capitals, as well as on the synergies and trade-offs between them. We gathered data on livelihood capitals through surveys (see Appendix A for the original surveys) because this allowed us to obtain both quantitative and qualitative data in a systematic way, providing enough data to compare charcoal producer livelihoods across governance regimes. We needed quantitative indicators to fulfill our research aim of studying because studying the effects of governance on differences between charcoal producer livelihoods, their trade-offs and their synergies required statistical tests to assess the significance of the observed differences, and to study correlations between different livelihood capitals to identify synergies and tradeoffs. On its turn, the qualitative data provided us with background information, in particular on potential causalities for observed trade-offs and synergies, which we used to interpret our quantitative results.

**Table 1.** Definition of and rational for the inclusion of livelihood capitals to understand the relationships between livelihoods of charcoal producers and the differences between OA-villages and CB-villages. We adapted the definitions of livelihoods of the framework of Scoones (1998) to charcoal production systems.

| Livelihood capital | Definition | Rationale for inclusion |
|---|---|---|
| Financial capital | Economic assets charcoal producers derive from charcoal production, including monetary assets and charcoal biomass. | Charcoal production provides primary or secondary income to purchase food, safe, and pay school fees and health care (Schure *et al* 2014). Charcoal itself is often used as a deposit for loans (Smith *et al* 2017), making charcoal a form of financial capital as well. We expect that financial capital synergizes with physical capital, as income may allow charcoal producers to invest in physical assets, such as housing (Smith *et al* 2017). Besides this, we expect that financial capital increases with access to human capital, specifically technical knowledge and skills regarding charcoal production and tree species that produce high quality charcoal (Schure *et al* 2019). We may expect a similar increase of financial capital with social capital because dense social networks could allow charcoal producers to exchange knowledge to improve their techniques (Smith *et al* 2017), as well as to collaborate, potentially allowing them to produce more charcoal and cut larger hardwood species, which have been found to produce high quality charcoal (Ndegwa *et al* 2018). Formal governance initiatives, such as charcoal producer associations, may enhance collaboration and knowledge exchange (Kamwilu *et al* 2021). Taxes from charcoal production collected in a communal fund and invested in community development projects are also a form of financial capital (Vyamana 2009). However, in this study we focus on the financial capital charcoal producers obtain individually. |
| Human capital | Knowledge, skills and health of charcoal producers, including technical knowledge and skills of charcoal production, the forest, and health risk (awareness). | Charcoal production requires specific skills and knowledge (Schure *et al* 2019), and its level influences the efficiency with which charcoal is produced (Andaregie *et al* 2020). Skills include the cutting of trees, the construction and lighting of a kiln, and the management of the kiln during the carbonization process to produce high quality charcoal (Schure *et al* 2019). Important knowledge includes (i) the type of species used to produce charcoal (Nisgoski *et al* 2014), (ii) the harvesting regime in place, and (iii) techniques used to produce charcoal. Charcoal production also demands good health, as it is a strenuous activity, |

| | | |
|---|---|---|
| | | requiring strength and fitness (Adebayo *et al* 2019, Kalaba 2013, Kazimoto 2015). The smoke from charcoal production may, however, be a health hazard (Oduor *et al* 2012) and charcoal producers may face risks of physical injuries, e.g., from fallen logs (Senya *et al* 2018). We expect that social capital, in particular dense social networks, enhances access of charcoal producers to knowledge that improves their skills and reduces health risks, hereby increasing their human capital. |
| Social capital | Social resources of charcoal producers, including their social networks, membership to associations, and perceived support from others. | Charcoal production requires limited social interactions, and charcoal producers often operate alone or in closed circles (Butz 2013). Yet, in some cases charcoal producers may rely on their social networks to collaborate with each other to produce charcoal and to manage forests (unpublished results). We expect that social capital influences knowledge exchange between charcoal producers and that it allows them to produce more charcoal through collaboration, positively influencing the income they obtain (Kamwilu *et al* 2021). On the one hand, enhanced collaboration may increase the rate of tree cutting because charcoal producers may together harvest larger trees at faster rates, which could affect forest resources, as observed for groups of migrant laborers in Mozambique (Baumert *et al* 2016). However, dense and decentralized social networks may also foster trust, adaptive capacity and knowledge exchange (Bhandari and Yasunobu 2009, Nenadovic and Epstein 2016, Nooteboom 2007), which has been shown to foster good governance of the forest in other social-ecological systems (Grafton 2005, Hawkins and Maurer 2010, Musavengane and Kloppers 2020). This process could potentially assure sustainable use of forest resources through effective governance (Vainio *et al* 2018). |
| Natural capital | Natural resources charcoal producers rely upon, including the woody biomass of the forest, specific species, and their functioning. | Charcoal producers harvest woody biomass from forests and plantations (FAO 2017, Ishengoma *et al* 2016). Some species produce higher quality charcoal than other species (Nisgoski *et al* 2014). The quality of charcoal can influence the price charcoal producers receive for the charcoal they produce (Nabukalu and Gieré 2019). Presence of large hardwood trees may, furthermore, cause charcoal producers to invest in tools, such as good axes and machetes or potentially chainsaws to allow them to cut trees (fast). Knowledge of charcoal producers about forests may allow them to select species, which could reduce the presence of specific species in the forest, potentially affecting the functional diversity of forests. Good governance that may result from dense and decentralized social networks (Grafton 2005, Hawkins and Maurer 2010, Musavengane and Kloppers 2020), could reduce forest degradation and deforestation, as could knowledge of sustainable charcoal production. |
| Physical capital | Physical assets of charcoal producers, including (the quality of) housing and charcoal production tools, such as axes and machetes. | Charcoal producers use part of the income they derive from charcoal production to build and improve houses (Smith *et al* 2017) and to buy tools for charcoal production (Luoga *et al* 2000). Hence, physical capital likely positively correlates with financial capital. Additionally, charcoal producers may feel the need to invest in tools for charcoal production if large trees are present in the forest. Purchase of efficient tools, such as chain-saws, may increase production rates (Agyeman *et al* 2012), potentially causing an increase in charcoal production and income. Besides this, physical capital may be enhanced on a community-level if taxes are collected from legal charcoal production by villages in a community development fund, which allows for investments in village infrastructure, such as access to roads and community buildings (e.g., classrooms, |

| | | |
|---|---|---|
| | | teachers' houses and village office buildings) (Lund 2007, Vyamana 2009). If community funds are invested in infrastructure, they may enhance access to forest resources, which may consequently foster higher rates of charcoal production. |

### *2.2.2 Data collection*

To collect data, we first developed livelihood surveys in English through an iterative and collaborative process. Tanzanian co-authors translated the surveys in Swahili to reduce risks of misinterpretation related to language and cultural differences. Three trial interviews were conducted to test the surveys and to provide final adjustments. We used the final surveys to obtain data on livelihood indicators for 160 charcoal producers, spread over the six study villages (Table 2). To assure a representative interviewee pool, we selected interviewees through stratified random sampling based on wealth status (Ravnborg 2003, Vyamana 2009). First, we asked Village Council members to provide a list of charcoal producers operating in their village. Second, we asked representatives of all sub-villages within each of the six villages to rank producers by wealth status during a workshop organized by the fieldwork team. We used the wealth status ranking approaches proposed by Ravnborg (2003) and Vyamana (2009), which resulted into three wealth classes (i.e., poorest, poor and non-poor). We chose to categorize charcoal producers in three wealth classes instead of four because charcoal production is an activity of the poor (Vollmer *et al* 2017). Hence, we expected limited charcoal producers that were less poor and non-poor and decided to pool them into one non-poor category. Finally, we organized the final list of charcoal producers per wealth status, and stratified the sample of interviewed charcoal producers (Table 2). Surveys were conducted in July and August 2020.

**Table 2.** Sampling size per wealth category for OA-villages and CB-villages. Unknown = Charcoal producers for which a wealth status could not be defined.

| | | **Number of respondents interviewed per wealth category** | | | | |
|---|---|---|---|---|---|---|
| | | **Poorest** | **Poor** | **Non-poor** | **Unknown** | **Total** |
| **CB-villages** | V1 | 13 | 24 | | | 37 |
| | V2 | 20 | 8 | | | 28 |
| | V3 | 9 | 17 | | | 26 |
| | **Sub-total** | 42 | 49 | | | 91 |
| **OA-villages** | V4 | 16 | 12 | | | 28 |
| | V5 | 9 | 6 | | 1 | 16 |
| | V6 | 11 | 10 | 1 | 3 | 25 |
| | **Sub-total** | 36 | 28 | | 4 | 69 |
| **Grand total** | | 78 | 77 | 1 | 4 | 160 |

The fieldwork team acquired permission during Village Council meetings to conduct interviews in the presence of members of the Village Council, one District government representative and, in the case of CB-villages, representatives of charcoal producer associations. Before commencing the interviews, we informed interviewees about the purpose of our study, indicated that their participation was voluntary, and told them that their names would remain anonymous. We also communicated that we would present the results of the study in academic journals and in the form of oral or poster presentations during conferences. Further, we developed an ethics-and-responsible-research-consent-form, which we translated into Swahili (Appendix A). We asked all interviewees to sign this form and for permission to be recorded, in line with guidelines on ethics and safety in fieldwork of the Geography Department of the University of Zurich (UZH). In case of illiteracy, the form was read out loud to the interviewees by a literate guide and charcoal producers gave oral consent. When interviewees were reluctant to answer specific questions or to be recorded, these survey questions were skipped and/or the interviewers refrained from recording. Interviewees were made aware that they could leave the study at any point.

We conducted fieldwork at the start of the Covid-19 pandemic, which prevented the lead and senior author of this paper to participate in person in Tanzania. Instead, fieldwork was carried out entirely by our Tanzanian co-author, Vincent Gerald Vyamana, and a fieldwork team under his lead (see acknowledgements), after ensuring that the field surveys could be conducted given country restrictions, personal exposure and ethical considerations. All members of the fieldwork team consented to carry out fieldwork because of their commitment to the research, the job opportunity it provided to them and the communities, and the low number of Covid-19 cases at the time of the fieldwork. During the Village Council meetings, protective measures for Covid-19 were adopted and remained in place at all times, namely wearing masks, using hand sanitizer and maintaining 1.5 m distance. The fieldwork team provided garbage cans to dispose of masks.

### *2.3 Data analysis*

#### *2.3.1 Integration of survey data into indicators*

We integrated the survey data of 41 survey questions into 19 quantitative livelihood indicators. Table 3 provides an overview of the indicators, the survey questions on which they were based and a rationale for inclusion. We selected indicators based on livelihood capital definitions and our rationale for including them (see Table 1). We designed the survey to inform indicators for each capital but we determined the final set of indicators following survey data processing (i.e., extracting survey data from the survey sheets and pooling it into one document) to account for data gaps (e.g., when a large proportion of producers did not wish to answer certain survey questions) and to make sure that the indicators provided quantitative information suitable for statistical analyses (i.e., enough variation to compare between study villages and to assess correlations). This was only possible after we processed survey data because only then we could produce an overview of the number of answers derived per survey question. Suitable indicators were discussed among all co-authors and those indicators that did not provide information that directly related to charcoal production activities were removed. Hereby, we mainly relied on the fieldwork experiences of the second co-author of this paper and his extensive knowledge on livelihoods in rural Tanzania. We did not adjust or alter indicators based on the results we obtained from our analyses. We included more human capital indicators than indicators for other capitals because of our broad definition of human capital (knowledge and skills, as well as the health of charcoal producers).

**Table 3.** Livelihood indicators, their units, a description and associated mechanism and hypotheses. The abbreviations for the indicators are used in the results section.

| | Indicator | Unit | Survey question | Answer | Rationale for inclusion |
|---|---|---|---|---|---|
| **Financial capital** | Income per bag (IpB) | Tanzanian Shillings (TZS) | **Q 5.3** How much money do you make per bag of charcoal? | Integer | ❖ *Description*: Income per bag reflects the net income charcoal producers derive by selling one bag of charcoal.<br>❖ *Mechanism & Hypothesis*: We expect higher income per bag in OA-villages than in CB-villages, because part of the income charcoal producers operating under CBNRM derive from charcoal is collected as a tax by the Village Council and put in a community fund, used to invest in community development projects and forest management. |
| | Charcoal bags per kiln (BpK) | Bags/kiln | **Q 5.2** How many bags of charcoal do you produce per kiln? | Integer | ❖ *Description*: Charcoal production reflects the number of charcoal bags obtained per kiln.<br>❖ *Mechanism & Hypothesis*: On the one hand, we expect an on average lower number of bags per kiln in CB-villages than in OA-villages because of forest harvesting quota. On the other hand, charcoal producers in CB-villages received training on charcoal production, which potentially enhanced the efficiency of their production practices and, hence, may have increased the number of charcoal bags they were able to derive per kiln. Further, in CB-villages charcoal producers may collaborate and build larger kilns, resulting in more bags per kiln. Besides this, charcoal producers in CB-villages are not allowed to overfill their charcoal bags, a practice that is very common in open access systems. This may also result in higher number of bags per kiln in CB-villages. |

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| | Charcoal production per year (CP) | Bags/year | **Q 4.4** How many kilns do you make per year? | Integer | ❖ *Description*: Average number of bags per kiln multiplied by the number of kilns per year. Hence, charcoal production (*CP*) was calculated as: <br> $CP = KpY * BpK$ <br> , where $KpY$ = kilns per year (Q 4.4), and $BpK$ = charcoal bags per kiln (Q 5.2). <br> ❖ *Mechanism & Hypothesis*: We expect lower charcoal production in CB-villages than in OA-villages because of the established harvesting quota. Alternatively, there could be higher charcoal production in CB-villages if charcoal is produced more efficiently, and if charcoal producers cooperate to produce charcoal. |
| | | | **Q 5.2** How many bags of charcoal do you produce per kiln? | Integer | |
| | Charcoal income (CI) | Tanzanian shillings (TZS)/year | **Q 4.4** How many kilns do you make per year? | Integer | ❖ *Description*: We calculated the total income each charcoal producer derives from charcoal production per year by multiplying the number of charcoal bags produced per year (*CP*) by the income derived per bag (*IpB*). Hence, charcoal income (*CI*) was calculated as: <br> $CI = KpY * BpK * IpB$ <br> ❖ *Mechanism & Hypothesis*: We hypothesize that charcoal producers in OA-villages derive more income per year from charcoal production than those in CB-villages because they might produce more bags per year and they can keep all income derived from charcoal to themselves, while charcoal producers in CB-villages share part of the income with the community. However, if charcoal production is more efficient in CB-villages more bags per kiln are produced and higher total income may be derived. |
| | | | **Q 5.2** How many bags of charcoal do you produce per kiln? | Integer | |
| | | | **Q 5.3** How much money do you make per bag of charcoal? | Integer | |
| **Human capital** | Health risk awareness (HRA) | Unitless | **Q 6.1** Does charcoal production pose a risk for your respiratory health? | Binary (yes/no) | ❖ *Description*: We measured the awareness of charcoal producers about the health risks they may face during production by summing the answers to three questions related to health risks. All questions had yes / no answers, which were converted into 1 (yes) or 0 (no). Health risk awareness (*HRA*) was then calculated as: <br> $HRA = RHR + PHR + SP$ <br> , where $RHR$ = awareness of respiratory health risks (Q 6.1), $PHR$ = awareness of physical health risks (Q 6.2), and $SP$ = safety precautions taken (Q 6.3). <br> ❖ *Mechanism & Hypothesis*: We hypothesize that charcoal producers in CB-villages are more aware of health risks than those in OA-villages, because they have access to health insurance paid from the community fund and are informed about health risks. |
| | | | **Q 6.2** Does charcoal production pose a risk for your physical health? | Binary (yes/no) | |
| | | | **Q 6.3** Do you take any safety precautions? | Binary (yes/no) | |
| | Faced health risks (FHR) | Unitless | **Q 6.4** Have you had any injuries from charcoal production? | Binary (yes/no) | ❖ *Description*: We calculated health risks faced by charcoal producers by summing the answers to three questions related to health risks charcoal producers faced. Two of these questions have yes/no answers, and one |

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| | | | **Q 6.6** How long did your injury reduce your ability to work? | Numeric | question produced answers in time in months. For the latter question, we normalized the data between 0 and 1 by dividing answers by the largest length of time an injury reduced their ability to work per village. Hence, faced health risk (*FHR*) was calculated as:<br>$FHR = ICP + KPI + normalized(LI)$<br>, where *ICP* = injuries obtained from charcoal production (Q 6.4), *KPI* = awareness of other charcoal producers that were injured during charcoal production (Q 6.10), and *LI* = amount of time injuries reduced ability to work (months) (Q 6.6).<br>❖ *Mechanism & Hypothesis*: On the one hand, we expect that training on efficient charcoal production and formalized cooperation in CB-villages reduces the amount of accidents. On the other hand, we expect that individual producers in OA-villages will use smaller logs because we expect limited collaboration between them, which challenges the cutting and carrying of heavy logs. This makes it less likely that charcoal producers in OA-village face health risks from large falling logs and injuries from sharp equipment, such as axes or machetes. |
| | | | **Q 6.10** Do you know of other producers who have been injured during charcoal production? | Binary (yes/no) | |
| | Technical knowledge (TK) | Unitless | **Q 7.5** Did you change your technique to improve the efficiency of charcoal production? | Binary (yes/no) | ❖ *Description*: We defined technical knowledge of charcoal producers as the sum of the answers to three questions (yes/no answers). Two questions provided an indication of the awareness of producers of different techniques for charcoal production, their ability to improve the quality of their charcoal, and their capacity to implement the techniques. Hence, technical knowledge (*TK*) was calculated as:<br>$TK = TC + TIQ + CTS$<br>, where *TC* = changes in production techniques to improve charcoal production efficiency (Q 7.5), *TIQ* = consideration of techniques to improve the quality of charcoal (Q 7.7), and *CTS* = consideration of tree species when producing charcoal (Q 7.10)<br>❖ *Mechanism & Hypothesis*: We hypothesize that the level of technical knowledge of charcoal production is relatively higher in CB-villages than in OA-villages because of the TTCS training scheme and extensive cooperation between charcoal producers in CB-villages. |
| | | | **Q 7.6** Do you consider any techniques to improve the quality of your charcoal? | Binary (yes/no) | |
| | | | **Q 7.10** Do you consider the species of a tree when you produce charcoal? | Binary (yes/no) | |
| | Production experience (PEx) | Years | **Q 4.1** How many years of experience in charcoal production do you have? | Integer | ❖ *Description*: We used the number of years a charcoal producer is engaged in charcoal production activities as a proxy for the experience they have with charcoal production.<br>❖ *Mechanism & Hypothesis*: We expect that charcoal producers in OA-villages have more experience with charcoal production than in CB-villages because producers that were new to charcoal production were trained under the TTCS project. Additionally, we |

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| | | | | | hypothesize that a charcoal producers' experience is positively related to their knowledge of charcoal production techniques, forest resources and the sustainability of their use. Charcoal producers with many years of experience will likely have a higher production efficiency because they have had time to improve their practices, which may consequently increase the income they derive per bag. |
| | Production efficiency (PEff) | Meters (m)/bag.kiln-1 | **Q 4.6** How big is the charcoal kiln you usually build?<br>**Q 5.2** How many bags of charcoal do you produce per kiln? | Numeric<br>Integer | ❖ *Description*: We combined the answers of two questions to calculate production efficiency. First, we calculated the size of the kiln as the sum of its length, width and height (Q 4.6). We did not calculate kiln volume because a relatively large percentage of charcoal producers did not provide an indication of the height of their kilns. Second, we divided the size of the kiln by the number of bags it produced (Q 5.2), i.e., the ratio between kiln size and bag. The smaller the kiln size/bag ratio, the more efficient charcoal production is. We then normalized the kiln size/bag ratio to values between 0 and 1. Finally, we subtracted the normalized kiln size/bag ratio from 1 to indicate production efficiency. Hence, production efficiency (*PEff*) was calculated as:<br>$Peff = 1 - norm(\frac{(KiL + KiW + KiH)}{BpK})$<br>, where $KiL$ = kiln length (m), $KiW$ = kiln width (m), $KiH$ = kiln height (m), $BpK$ = bags per kiln, and norm = normalized.<br>❖ *Mechanism & Hypothesis*: We hypothesize higher production efficiency in CB-villages than in OA-villages because the training programs were geared towards higher carbonization efficiency and at higher efficiency more charcoal could be produced from the same forest biomass stocks. |
| **Social capital** | Cooperation with others (CwO) | degree | **Q 9.2** With who of the charcoal producers to you prefer to work?<br>**Q 9.4** Who are the other charcoal producers you work with? | Factor<br>Factor | ❖ *Description*: We calculated the number of other charcoal producers interviewees worked with per village. We did this by linking the names of interviewed charcoal producers with those charcoal producers they worked with. This allowed us to link the names they mentioned to each other to create an edge and node list, which we used to compute the degree metric, which indicates the number of collaborations between charcoal producers.<br>❖ *Mechanism & Hypothesis*: We hypothesize that charcoal producers collaborate more with each other in CB-villages than in OA-villages because charcoal producer associations and collaborate with each other through the participatory charcoal production scheme in place. |
| | Interaction formality (IF) | Unitless | **Q 15.1** Are you a member of a charcoal producer association? | Binary (yes/no) | ❖ *Description*: We defined interaction formality as the level to which charcoal producers interact with each other through membership of and/or engagement in associations that were formally established through the harvesting plan and recognized |

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|  |  |  | **Q 15.3** Do you take part in the decision making process of the charcoal producer association? | Binary (yes/no) | by the Village Council and District Council. We combined the answers to three questions to calculate the formality of interactions of charcoal producers, namely (i) membership to charcoal producer associations, (ii) decision making in charcoal producer associations, and (iii) membership to other associations. All answers were given equal weights. Hence, we calculated interaction formality (*IF*) as:<br>$IF = MA + DA + OA$<br>, where *MA* = membership a charcoal producer association (Q 15.1), *DA* = decision making in charcoal producer associations (Q 15.3), and *OA* = membership to other associations (Q 15.4).<br>❖ *Mechanism & Hypothesis*: We expect that formality of interactions enhances cooperation between charcoal producers in CB-villages, where formal institutions are constructed through participatory forest management. In OA-villages, we expect low interaction formality, as charcoal production is considered illegal in these villages. |
|  |  |  | **Q 15.4** Are you a member of another community association? | Binary (yes/no) |  |
|  | Support (Sup) | Unitless | **Q 15.9** Do you feel supported by other villagers? | Binary (yes/no) | ❖ *Description*: We combined the answers to four questions to calculate the level of support experienced by charcoal producers, namely (i) support experienced from their fellow villagers, (ii) their Village Council through the VNRC responsible for the management of forest use, (iii) the District government, and (iv) Tanzania Forest Service. Hence, we calculated support (*Sup*) as:<br>$Sup = SupO + SupV + SupD + SupT$<br>, where *SupO* = support experienced from other villagers (Q 15.9), *SupV* = support experienced from the VNRC (Q 15.10), *SupD* = support experienced from the District government (Q 15.12), and *SupT* = support experienced from the Tanzania Forest Service (15.13).<br>❖ *Mechanism & Hypothesis*: We expect higher support in CB-villages than in OA-villages because of formalization of interactions through charcoal producer associations and participatory forest schemes. Yet, we may nevertheless expect relatively high support in OA-villages because of cultural norms that foster support among people in Tanzania (personal communication Vincent Gerald Vyamana, 2022). |
|  |  |  | **Q 15.10** Do you feel supported by the village committee? | Binary (yes/no) |  |
|  |  |  | **Q 15.12** Do you feel supported by the district government? | Binary (yes/no) |  |
|  |  |  | **Q 15.13** Do you feel supported by the Tanzania Forest Service? | Binary (yes/no) |  |
| **Natural capital** | Forest impact awareness (FIA) | Unitless | **Q 7.11** Do you take the state of the forest into consideration when you produce charcoal? | Binary (yes/no) | ❖ *Description*: We calculated forest impact awareness (*FIA*) by summing the answers to two questions:<br>$FIA = CSF + MIC$<br>, where *CSF* = consideration of the state of the forest when producing charcoal (Q 7.11), and *MIC* = awareness on ways to minimize the |
|  |  |  | **Q 7.12** Do you know | Binary (yes/no) |  |

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| | | | how to minimize the impact of charcoal production on the village forest? | | impact of charcoal production on the village forest (Q 7.12).<br>❖ *Mechanism & Hypothesis*: We expect higher forest impact awareness in CB-villages than OA-villages because of the training charcoal producers are subjected to in CB-villages. |
| | Past forest sustainability (PFS) | Unitless | **Q 8.5** In your view; Did the amount of wood in the forest change over the past 5 years? | Multiple choice (-1 to 1) | ❖ *Description*: We calculated past forest sustainability by summing answers of two questions on changes in the amount of wood in the forest over the past 5 years, and changes in the number of trees that produce quality charcoal over the past 5 years. Hence, we calculated past forest sustainability (*PFS*) as:<br>$$PFS = CWF + CQT$$<br>, where *CWF* = perceived changes in the amount of wood in the forest over the past 5 years, and *CQT* = perceived changes in the number of trees that produce quality charcoal over the past 5 years.<br>❖ *Mechanism & Hypothesis*: We hypothesize that charcoal producers in CB-villages have a more positive perception of change in the amount of wood and quality species than producers in OA-villages because of the harvesting plan in place and enhanced knowledge exchange about production and forest management through high levels of collaboration. |
| | | | **Q 8.6** In your view; Did the number of trees that produce quality charcoal change over the past 5 years? | Multiple choice (-1 to 1) | |
| | Future forest sustainability (FFS) | Unitless | **Q 8.3** In your view; Is there enough wood available to you in the village to continue producing charcoal over the next 10 to 20 years? | Binary (yes/no) | ❖ *Description*: To calculate future forest sustainability, we summed the answers to two questions on: (i) the continuation of available biomass for charcoal production, and (ii) the speed of forest regeneration. Hence, we calculated future forest sustainability (*FFS*) as:<br>$$FFS = WCP + RCP$$<br>, where *FFS* = the perception of charcoal producers on the availability of wood to produce charcoal from in the next 10 to 20 years, *WCP* = the perception charcoal producers on the whether the speed of forest regeneration allows charcoal production to continue over the next 10 to 20 years.<br>❖ *Mechanism & Hypothesis*: We expect more positive perceptions on future forest sustainability in CB-villages because of the harvesting plan in place, which aims to mitigate forest degradation and deforestation. In contrast, we expect overexploitation of forests in OA-villages due to unregulated production, resulting in more negative perceptions on future forest sustainability. We also expect that future forest sustainability positively relates to past forest sustainability because demand for charcoal will remain high. |
| | | | **Q 8.4** In your view; Does the village forest regenerate fast enough for charcoal production to continue over the next 10 to 20 years? | Binary (yes/no) | |
| | Distance from forest (DF) | Kilometers (km) | **Q 8.1** How far is the nearest forest from your house? | Numeric | ❖ *Description*: Distance from forest (*DF*) was measured as the distance in kilometers that charcoal producers have to walk to obtain the forest resources they need to produce |

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| | | | | | charcoal. Charcoal producers used different units to indicate the distance to the forest (e.g., kilometers, hours or minutes) and some cycle to the forest instead of walk. We assumed an average walking speed of 5 km per hour and an average cycling speed of 15 km an hour to calculate distance from the forest in kilometers.<br>❖ *Mechanism & Hypothesis*: We expect a higher distance to the forest in OA- villages than CB-villages, because we expect forests to be depleted near the center of OA-villages. |
| **Physical capital** | Access to housing (AtH) | Unitless | **Q 16.2** How many houses do you own? | Integer | ❖ *Description*: We calculated access to housing by summing the answers to two questions on: (i) the number of houses a charcoal producer owns and (ii) the number of new houses the charcoal producer constructed over their lifetime. Hence, access to housing (*AtH*) was calculated as:<br>$AtH = HO + HC$<br>, where *HO* = the number of houses a charcoal producer owns, and *HC* = the number of houses a charcoal producer constructed over their lifetime.<br>❖ *Mechanism & Hypothesis*: We hypothesize higher access to housing in OA-villages than in CB-villages because we expect higher income from charcoal production in OA-villages. |
| | | | **Q 16.3** How many new houses did you construct over your lifetime? | Integer | |
| | Housing quality (HQ) | Unitless | **Q 16.4** What material are your walls made of? | Multiple choice (1 to 3) | ❖ *Description*: We calculated housing quality by summing the answers to three questions on: (i) the wall material, (ii) the roof material, and (iii) the floor material of the house of the interviewed charcoal producer. Hence, we calculated housing quality (*HQ*) as:<br>$HQ = WM + RM + FM$<br>, where *WM* = the material from which the walls of the charcoal producer's house is made, *RM* = the material from which the roof of the charcoal producer's house is made, and *FM* = the material from which the floor of the charcoal producer's house is made.<br>❖ *Mechanism & Hypothesis*: We hypothesize higher housing quality in OA-villages than in CB-villages because we expect the income from charcoal production to be higher in OA-villages, and expect them to partially invest this income in housing. |
| | | | **Q 16.5** What material is your roof made of? | Multiple choice (1 to 3) | |
| | | | **Q 16.6** What material is your floor made of? | Multiple choice (1 to 2) | |

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|---|---|---|---|---|---|
| | Access to tools (AT) | Unitless | **Q 4.9** What equipment do you use when producing charcoal? | Integer | ❖ *Description*: Access to charcoal producer tools refers to the types of tools charcoal producers use to produce charcoal. Hence, we calculated access to charcoal production tools (AT) as:<br>$AT = \sum T_{tool}$<br>, where $T_{tools}$ = a charcoal production tool mentioned by the interviewed charcoal producers.<br>❖ *Mechanism & Hypothesis*: We hypothesize that charcoal producers in OA-villages own a larger number of tools because we expect them to receive higher income from charcoal. |

### *2.3.2 Comparing livelihood capitals between open access and CBNRM*

We examined whether differences in livelihood capitals between OA-villages and CB-villages occurred. To do so, we rescaled the livelihood indicator data to range between 0.1 and 1, to assure the statistical comparability of indicators. We used the following transformation (De Leijster *et al* 2019, Kearney *et al* 2019):

$$Y_i = 0.1 + \left(\frac{x_i - min_i}{max_i - min_i}\right) * 0.9$$

, where *i* = the livelihood capital, *Y* = the rescaled indicator for livelihood capital *i*. *Min* and *max* reflect the minimum and maximum value of livelihood capital *i*. For each livelihood capital indicator, we removed those charcoal producers that did not provide sufficient answers to the survey questions integrated in the indicator. This resulted in different pools of charcoal producers per indicator. The number of charcoal producers per village used in the analyses per indicator can be found in Appendix Table A1. Prior to analysis, we tested for normality, using histograms and the Shapiro Wilk test. Since none of the livelihood indicators data were normally distributed and normality could not be derived through transformations, we used the non-parametric Kruskal-Wallis test (Breslow 1970) to determine whether OA-villages and CB-villages differed in their livelihood capitals. We displayed the average livelihood capital indicator values in a radar plot.

### *2.3.3 Synergies and trade-offs between livelihood capitals*

We calculated the pair-wise Spearman rank correlation per village (Zar 1972), per village type and for all data combined. We included all indicators in this analysis, except for charcoal income (CI) because many charcoal producers were unable to provide an estimate on the number of kilns they create per year. Hence, upon inclusion, income per bag would have resulted in a large reduction of the charcoal producer sample included in the Spearman rank correlation. The relatively smaller data sample for charcoal income was due to cultural reasons and because the decision to produce charcoal depends on financial needs of charcoal producers. Although we included all other livelihood capital indicators, the interaction formality (IF) indicator did not produce enough variation in OA3 to assess its correlation to other indicators. Therefore, this indicator was not included in the Spearman correlation of OA3. Yet, the interaction formality data of OA3 was included in the Spearman correlation when assessing all villages combined and the project and non-project villages together. The total number of charcoal producers per village included in the Spearman correlation matrix and the PCA can be found in Appendix Table A1. In the results section, we only discuss correlation values larger than 0.3 and smaller than -0.3 rho because these correlations are widely considered to be moderate to strong (Akoglu 2018).

To better understand trade-offs between livelihood capital indicators, we conducted a Principal Component Analysis (PCA) on the same dataset as the Spearman rank correlation. A PCA is a method that differentiates the number of independent dimensions (i.e., orthogonals) in a data set, by identifying axes that combine the original variables to minimize information loss (Wold *et al* 1987). Therefore, a PCA serves to reduce dimensionality. First, we scaled the variables to assure each variable contributes equally to the analysis. We used the "scale" function of the R-package "base", which scales each input per variable by subtracting the mean and dividing it by the standard deviation of the variable. Second, we computed a covariance matrix, including all variables. Third, we computed eigenvalues and eigenvectors of the covariance matrix, which corresponded to principal components, with the first principal component containing the maximum information, followed by the second and so on (Abdi and Williams 2010, Wold *et al* 1987). We color coded the data per village and plotted ellipses for each of the six study villages in the PCA, using an ellipse level of 0.5. We also plotted such ellipses for wealth status and gender of charcoal producers.

We conducted all data analyses in R (Team 2019).

## 3. Results

### *3.1 Comparing livelihood capitals between open access and CBNRM*

We found significant differences between the livelihood capitals of charcoal producers in OA- and CB-villages (Fig. 3 and 4). On average, charcoal producers in CB-villages had a higher perceived sustainability of past and future forest use (PFS, FFS), produced on average more bags per kiln (BpK), had more formal interactions (IF), and showed more cooperation with others (CwO) than producers in OA-villages. On the other hand, the quality of the houses (HQ) of charcoal producers and income per bag (IpB) was significantly higher in OA-villages than in CB-villages. Generally speaking, all other livelihood indicators did not differ significantly between OA-villages and CB-villages but we observed some variation between villages.

Generally, we did not find consistently higher or lower indicator values per capital between the two governance regimes because we observed differences between indicators of the same capital in total and per village (type) (Fig. 3 and 4). For natural capital, we found a wide range of variability in forest impact awareness for both OA-villages and CB-villages. For financial capital, we found that charcoal produced per year (CP) was significantly higher in CB1 and CB2 than in OA-villages (Fig. 5). For human capital, we found higher technical knowledge (TK) in CB1 and CB2 compared to OA-villages. We also found significantly higher production efficiencies (PEff) in CB3 and OA3 compared to other villages, and for the other indicators we found a mix between OA-villages and CB-villages, indicating that the two governance regimes produced similar outcomes for some of the indicators. We found no differences in livelihood capital indicators between wealth categories (poor and poorest) and between genders (male and female) (Appendix Fig. A1).

### *3.2 Synergies and trade-offs between livelihood capitals*

We found a strong separation between CB-villages and OA-villages along PC1, with OA-villages being most associated with income per bag (IpB) on the right-hand side of PC1, while past and future forest sustainability awareness (PFS, FFS), bags per kiln (BpK), cooperation with others (CwO), technical knowledge (TK), and support (Sup) were more aligned with CB-villages on the left-hand side of PC 1 (Fig. 6a). The second axis (PC2) separated production efficiency (PEff) from forest impact awareness (FIA), and produced some separation between CB-villages. We presented the Spearman correlation values between livelihood indicators in Fig. 6b. Overall, we found synergies (positive correlations) between natural and social and financial capitals, and between financial capital and all other capitals, except physical capital. Strong trade-offs (negative correlations) emerged between income per bag (IpB) and most other capital indicators, as well as between production efficiency (PEff) and forest impact awareness (FIA).

When examining the correlation between livelihood indicators for each village type (Fig. 6c and 6d), we observed both more synergies in CB-villages and more trade-offs in OA-villages. The strongest synergies in CB-villages occurred between charcoal bags per kiln (BpK) and production efficiency (PEff), between support (Sup) and financial capital indicators and interaction formality (IF), past forest sustainability (PFS), future forest sustainability (FFS), as well as housing quality (HQ), and between past and future forest sustainability. In OA-villages, the strongest synergies occurred between interaction formality (IF) and distance to forest (DF), between charcoal bags per kiln (BpK) and production efficiency (PEff), and between income per bag (IpB) and access to tools (AT). The strongest trade-offs in CB-villages occurred between (i) health risk awareness (HRA) and income per bag (IpB),

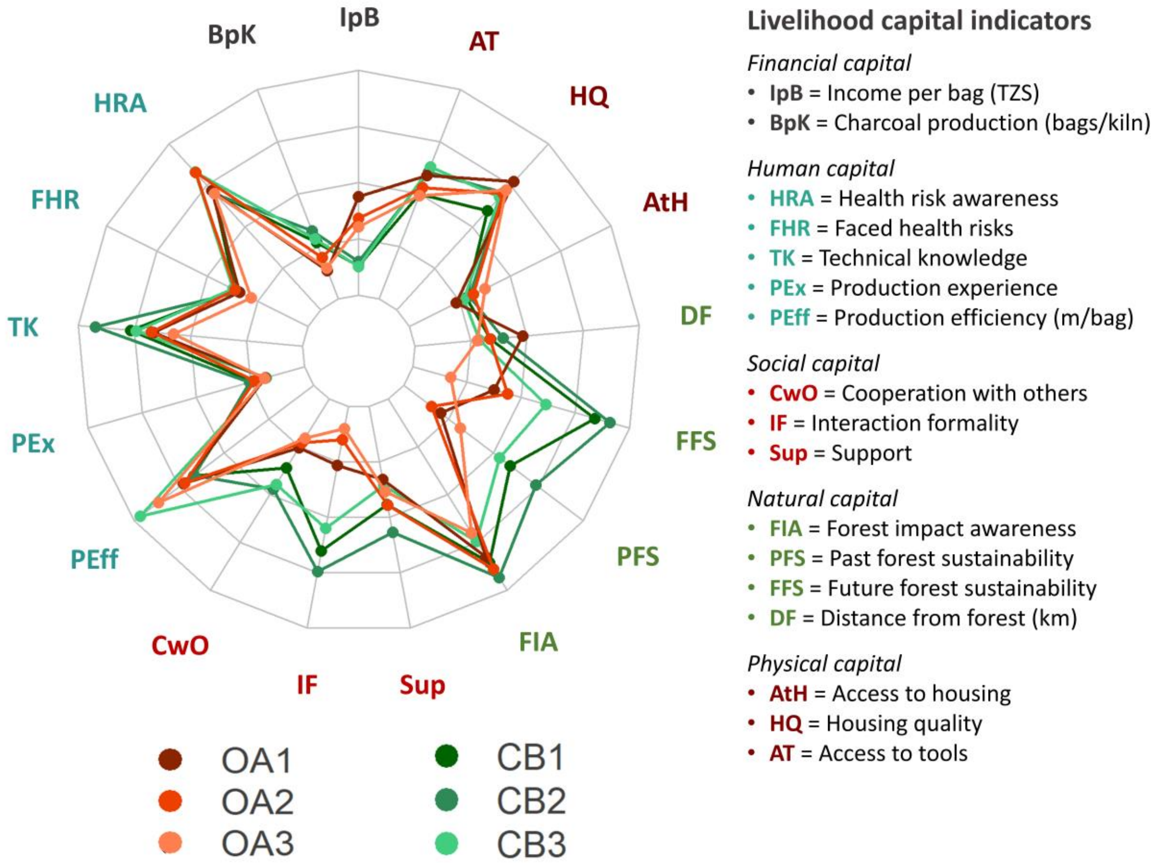


**Figure 3.** Average charcoal producer livelihood capital indicators per village. CB-villages are under community-based natural resources management (CBNRM), while OA-villages are under open access. An explanation of each livelihood capital indicator and a rationale for their inclusion can be found in Table 3, which follows the same color-code scheme. See Fig. 4 for statistical differences between villages, and Appendix Table A2 and A3 for the p-values derived through the Kruskal-Wallis test.

future forest sustainability (FFS), as well as housing quality (HQ), (ii) production experience (PEx) and production efficiency (Peff), and (iii) production efficiency (PEff) and forest impact awareness (FIA). For OA-villages, we observed trade-offs between (i) health risk awareness (HRA) and production efficiency (PEff), as well as cooperation with others (CwO), (ii) income per bag (IpB) and access to housing (AtH), (iii) past forest sustainability (PFS) and forest impact awareness (FIA), (iv) access to housing (AtH) and cooperation with others (CwO), as well as access to tools (AT). Interestingly, trade-offs and synergies between livelihood capital indicators differed between villages with the same governance regime (Appendix Fig. A2).

## 4. Discussion

In this study, we set to understand the effect of two forest governance regimes – open access and CBNRM – on access to and trade-offs and synergies between charcoal producer livelihoods. We find that governance can alter access of charcoal producers to indicators of the majority of livelihood capitals, indicating that transitions from open access to CBNRM and vice versa have the power to shape livelihoods. Yet, strong tradeoffs between certain forms of financial capital (income per bag) and other capitals under CBNRM indicate that governance can enhance access to certain livelihood capitals at the expense of others. More specifically, it confirms our hypothesis that the introduction of CBNRM, in

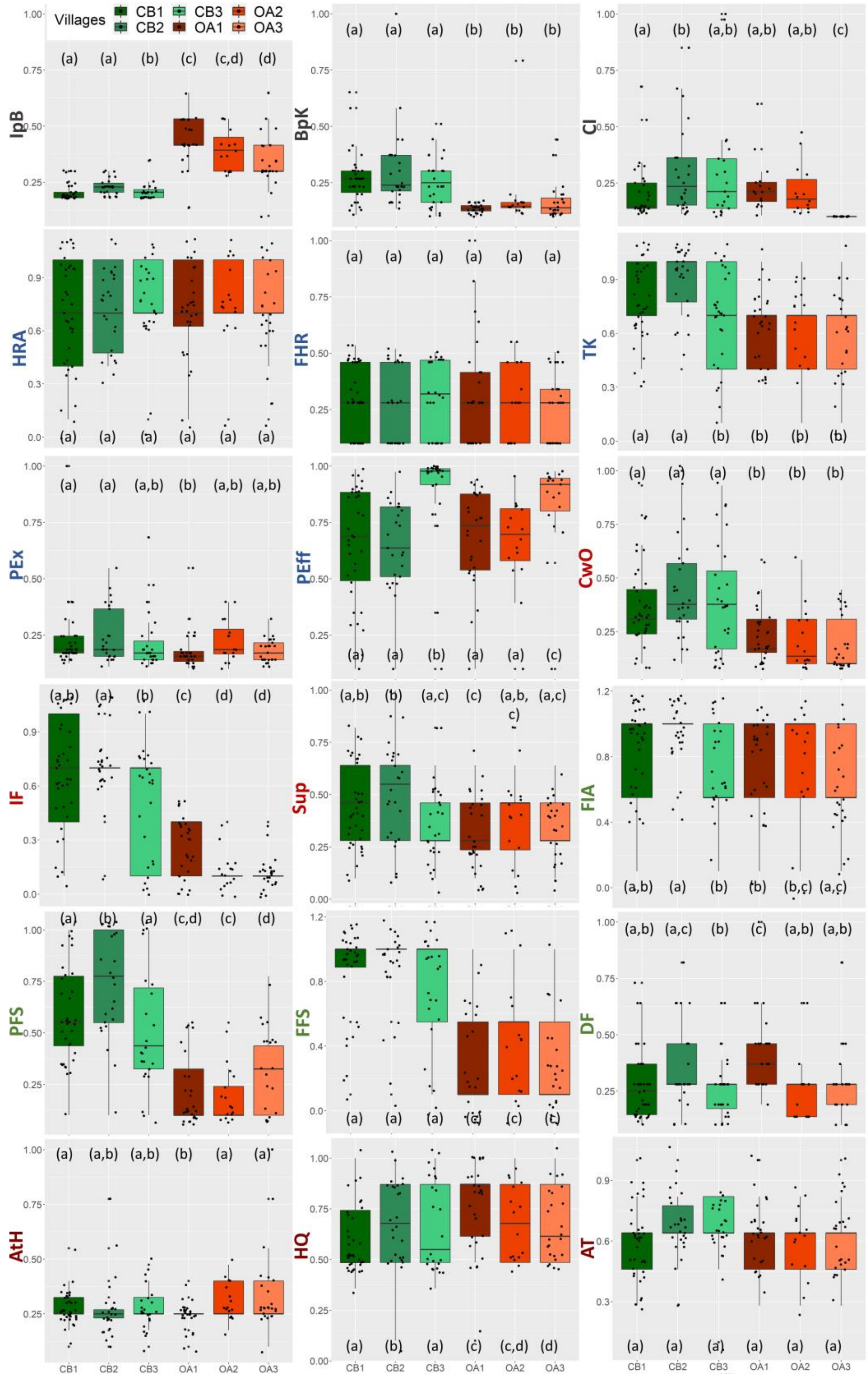


**Figure 4.** Boxplots of livelihood capital indicators per village. The color codes of the y-axis labels are in line with the color scheme of Table 3. Significantly different groups identified through a Kruskal-Wallis test are indicated with a letter, where similar letters indicate similar groups and vice-versa. The results of the Kruskal-Wallis tests are presented in Appendix Table A3.

particular the revenue-sharing system, transforms financial capital into other types of capital through investments in forest management and development. We also observe synergies and tradeoffs

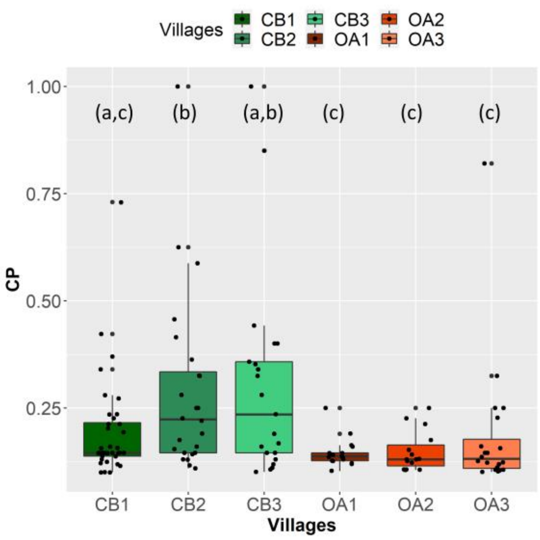


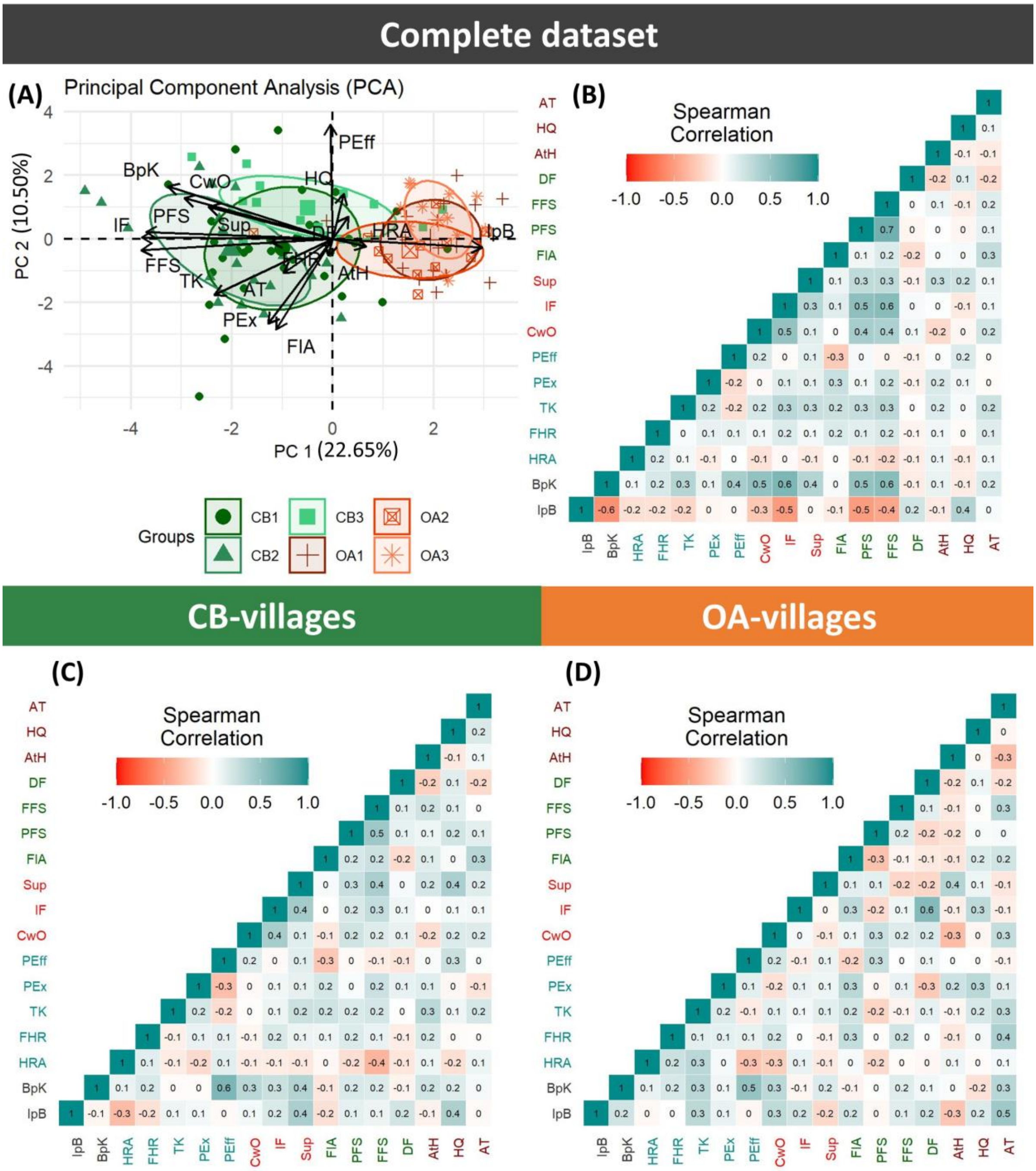
**Figure 5.** Charcoal production per year (CP) per study village. Significantly different groups are indicated with a letter, where similar letters indicate no significant differences between groups and vice versa. The results of the Kruskal-Wallis tests are presented in Appendix Table A2. Note that this indicator could not be included in the PCA analysis and therefore we chose to display it in this separate boxplot.

between indicators of the same capitals, suggesting that livelihood capitals are not singular and that enhancing one aspect of a livelihood capital does not automatically raise other aspects. This finding calls for holistic analyses of livelihoods by scientists and policy makers to better understand their response to governance, through the recognition of trade-offs and synergies. Finally, we observe that trade-offs and synergies among livelihood capitals vary between villages under similar governance regimes, indicating that governance is not the main determinant of livelihood capital interactions and that other social-economic or ecological factors may play a role, such as culture or tree biodiversity.

### *4.1 Comparing livelihood capitals between open access and CBNRM*

We hypothesized that charcoal producers operating under open access and CBNRM governance regimes have different access to livelihood capitals. We expected (i) higher natural capital under CBNRM than open access because the CBNRM harvesting plan aims at mitigating deforestation and forest degradation related to the production of charcoal and other forest products, (ii) higher social and human capital under CBNRM than open access because CBNRM includes training sessions and formal institutions that may enhance interactions between charcoal producers themselves and with members of their governments, and (iii) lower financial capital under CBNRM than open access because part of the income charcoal producers derive under this scheme is shared in a community fund, used for forest management and community development projects, which transforms financial capital into other livelihood capitals. Our findings partly support these hypothesis because we find indications for higher natural capital and social capital, as well as lower financial capital under CBNRM than open access. Yet, not all indicators reveal this trend and we find limited effects of governance on human capital indicators, although the effect on human capital at community level may nevertheless be substantial due to communal health care coverage under CBNRM.

For natural capital, we find that CB-villages exhibit higher perceived forest sustainability and higher forest impact awareness than in OA-villages. Higher perceived forest sustainability may indicate more sustainable forest use in CB-villages than OA-villages. This may have been fostered by investments of taxes from the community development fund into forest management, which enhances the quality of forest governance in CB-villages. This finding is in line with studies that show reductions in deforestation and forest degradation (Gobeze *et al* 2009) or an increase in forest area (Blomley *et al* 2008, Takahashi and Todo 2012) under CBNRM, and contrasts with studies that find continued deforestation and forest degradation upon the introduction of CBNRM (Treue *et al* 2014). Nevertheless, perceptions of sustainable forest use may deviate from the actual sustainability of forest use related to differentiations in the ways local communities and external parties understand sustainable forest management (Matta and Alavalapati 2006). For instance, in Kilosa District, communities understand forest processes based on the size of trees and ecological functioning, where big trees and abundant availability of mushrooms are indicative of a healthy forest (personal communication Vincent Gerald Vyamana, 2022). Hence, promotion of selective cutting under CBNRM may provide charcoal producers with a sense of sustainable forest use, even if actual harvesting rates exceed forest regeneration rates. In contrast, charcoal production in OA-villages often occurs through clear cutting, resulting in a loss of all large trees; thus potentially causing perceived unsustainable charcoal production in these villages, even if harvesting rates do not exceed regeneration rates in OA-



- **IpB** = Income per bag (TZS)
- **BpK** = Charcoal bags per kiln (bags/kiln)
- **HRA** = Health risk awareness
- **FHR** = Faced health risks
- **TK** = Technical knowledge
- **PEx** = Production experience
- **PEff** = Production efficiency (m/bag)
- **CwO** = Cooperation with others
- **IF** = Interaction formality
- **Sup** = Support
- **FIA** = Forest impact awareness
- **PFS** = Past forest sustainability
- **FFS** = Future forest sustainability
- **DF** = Distance from forest (km)
- **AtH** = Access to housing
- **HQ** = Housing quality
- **AT** = Access to tools

**Figure 6.** Synergies and trade-offs between livelihood capital indicators of charcoal producers (a, b), and for CB-villages (c), and OA-villages (d) separately.

village boundaries. Charcoal producers in OA-villages may also associate impacts of land clearing for agriculture to perceived forest sustainability rather than forest use for charcoal production (Doggart *et al* 2020), a practice that is controlled in CB-villages (Lund 2007, Mustalahti and Lund 2010). Interestingly, charcoal producers in both village types show similar forest impact awareness, suggesting that an awareness of the unsustainability of charcoal production does not necessarily stimulate charcoal producers to transition to, in their eyes, more sustainable tree harvesting practices, even upon perceived unsustainable forest use in the past. It may also suggest that charcoal producers are generally aware of the effects charcoal production has on their village forest, may it be through experience or through communication with others, which is not surprising as local knowledge of forest dynamics and biodiversity is often high in rural communities (Nura and Endris 2020, Selemani 2020, Solomon *et al* 2018).

For social capital, we find that CB-villages exhibit higher interaction formality (IF) and cooperation with others (CwO) than OA-villages, likely due to participation in training schemes, membership to charcoal producer associations, and participatory forest management practices facilitated through the CBNRM regime. Higher social capital may induce trust, adaptive capacity and reciprocity in CB-villages (Bhandari and Yasunobu 2009, Nenadovic and Epstein 2016, Nooteboom 2007), which could ultimately improve forest governance (Grafton 2005, Hawkins and Maurer 2010, Musavengane and Kloppers 2020). Higher levels of trust through increased collaboration may increase perceived past and future forest sustainability in CB-villages, as charcoal producers may trust that the harvesting plan in place sustains their forests and that fellow charcoal producers adhere to it. Alternatively more positive perceptions of forest sustainability may elicit unfounded trust that charcoal production occurs sustainably in CB-villages because charcoal producers may experience a healthy forest even upon unsustainable harvesting rates. While charcoal producers cooperate more in CB-villages, they do not experience higher levels of support by their fellow villagers, the Village Council, District Council and national forest agency than those operating in OA-villages. As it is culturally accepted to ask for support from others in Tanzania, and people may be perceived as an outlier in society if they do not support others (personal communication Vincent Gerald Vyamana, 2022), charcoal producers may naturally provide each other the support they need to sustain their livelihoods in both village types.

For human capital, we observe significantly higher technical knowledge and a higher number of bags per kiln in CB-villages than in OA-villages, likely obtained through formal training and oral transmission fostered by enhanced interactions under CBNRM. Based on this result, we would have expected that charcoal producers in CB-villages operationalize their high levels of technical knowledge by producing charcoal in a more efficient way, resulting in higher numbers of bags per kiln. However, we find higher production efficiency in CB-villages than in OA-villages, which may be due to an already abundant local experiential knowledge that is culturally determined. However, charcoal producers may also have misinterpreted our questions on human capital. For instance, charcoal producers may not consider the smoke from charcoal kilns hazardous but rather perceive the dust as a health risk because it leaves a visible layer on their clothes, skin and nasal cavity (personal communication Vincent Gerald Vyamana, 2022). Besides this, we did not document knowledge on laws, rules and regulations on forest use and conservation, which often lacks in rural communities (Appiah *et al* 2021, Timothy *et al* 2016) and could have produced deviations between OA-villages and CB-villages as a result of the TTCS project. This indicates the potential susceptibility of the outcome of the SLA to indicator selection and the importance of acknowledging potential gaps in the livelihood analyses to assure a cautious interpretation of results.

For financial capital, our results partly corroborate our expectation that charcoal producers in CB-villages have lower financial capital that those in OA-villages because we find a significantly lower income per bag in CB-villages. The main explanation for a lower income per bag is tax collection from intermediates under CBNRM by the Village Council, and the avoidance of taxes under open access. Due to the implemented tax scheme, intermediates pay an overall higher price per bag under CBNRM than under open access, despite the higher income charcoal producers receive per bag in OA-villages. Conversations with Village Council members revealed that the high price difference per bag makes it difficult to attract sufficient intermediates to purchase charcoal produced under CBNRM because buyers prefer cheap bags in order to make more income. This explains why charcoal producers in CB-villages sell charcoal to one specific intermediate, which they call by name, while charcoal producers in OA-villages sell charcoal to many different intermediates. This lack of competition may potentially challenge price negation with intermediates in CB-villages, as has been observed in studies that reveal a strong brokering role for transporters and wholesalers in determining prices for charcoal bags in the charcoal value chain (Agyei, Hansen, and Acheampong 2018; Baumert et al. 2016; Kazimoto 2015).

The differences in income per bag observed between OA-villages and CB-villages reveal challenges in fostering transitions to legal charcoal production in villages that neighbor villages where illegal production reduces costs for intermediates. Such challenges may have consequences for the livelihoods of charcoal producers, which we find evidence for in our study, as several interviewed charcoal producers in CB-villages indicated that they stopped producing charcoal because of the low prices they received per bag. A reduction of legal charcoal production under CBNRM may ultimately threaten the continuation of the scheme and the forest management and community development benefits it provides. At present, unregulated or unregistered charcoal production in Tanzania results in a loss of about 100 million USD per year in tax money, which could have been invested in forest management (WB 2010a). Previous studies show that participatory forestry fosters widespread tax collection at a local scale, with significant potential to enhance the amount of taxes received from forest products in Tanzania (Lund 2007). Hence, it is important to promote the continuation and expansion of CBNRM to avoid competition in prices between CBNRM and open access (e.g., based on the TTCS scheme) and/or to assure that illegal charcoal production is being mitigated in open access villages surrounding villages under CBNRM.

Despite the higher income per bag in OA-villages, we find that this income does not translate in higher physical capital, except for housing quality. Several reasons could explain this mismatch. First, it is not clear whether producers directly use charcoal income to build new houses or to improve them, indicating the need to specify the use of charcoal revenue in future studies. For instance, it could be that charcoal revenue is invested in education or health care instead, as observed in previous studies (Jones, Ryan, and Fisher 2016; Smith, Hudson, and Schreckenberg 2017), although this is not common under open access in Tanzania (Lund 2007). Second, although charcoal producers operating in OA-villages may receive more income per charcoal bag, they may also face higher costs. For example, charcoal producers in OA-villages may face risks of fines or discharge of their charcoal bags when caught by enforcers. Third, charcoal producers often only produce charcoal when needed because charcoal often provides secondary or complementary income (Smith, Hudson, and Schreckenberg 2017; Jones, Ryan, and Fisher 2016). Charcoal producers also indicated that they find the work physically constraining and dangerous, and that they would not continue the practice if they had an alternative; a sentiment that is often discussed in literature (Adebayo *et al* 2019, Kalaba 2013, Kazimoto 2015). Fourth, comparable levels of physical capital between the two governance regimes may result from the low overall wealth status of charcoal producers (Baumert *et al* 2016, Zorrilla-Miras *et al* 2018). Charcoal production is known as an activity of the poor (Schure *et al* 2014), and once producers obtain more income they often transition to other businesses (e.g., they become intermediates) (Jones, Ryan, and Fisher 2016; Smith, Hudson, and Schreckenberg 2017; Vollmer et al. 2017). Finally, we only assessed physical capital at individual level. It is likely that the CBNRM revenue-sharing scheme enhances investments in physical capital at the community scale, resulting in an overall higher physical capital in CB-villages than OA-villages.

Surprisingly, we did not find clear differences between wealth classes nor between male and female charcoal producers. These findings contrast with previous studies, which show that poor forest users are often unable to take full advantage of the benefits CBNRM provides (Vyamana 2009), and that female producers are often marginalized in the charcoal production value chain (Ihalainen *et al* 2020).

### *4.2 Synergies and trade-offs between livelihood capitals*

We find trade-offs and synergies between livelihood capitals under both governance regimes, which differ between the two village types and even between villages of the same type, indicating that livelihood capital interactions respond to both the governance system in place and local social-ecological circumstances. We also find trade-offs and synergies between indicators of the same livelihood capital, suggesting that livelihood capitals are not independent and that enhancing one aspect of a livelihood capital does not automatically enhance other aspects. This finding raises questions about the advantage of categorizing livelihood assets, which echoes previous criticism on categorization (Scoones 2009). Additionally, and not surprisingly, our study confirms complexities in fostering all livelihood capitals necessary to build a sustainable livelihood (Fang *et al* 2014, Kumar and Luna 2018). It is important to further investigate implications of livelihood trade-offs because some capitals may be more suitable to enhance livelihood sustainability than others (Kumar and Luna 2018) and because some livelihoods are more sensitive to the loss of one capital than to a loss of others (Fang *et al* 2014). Finally, the trade-offs and synergies observed in this study likely change over time (Lade *et al* 2017) and respond to shocks, such as climate change induced extreme weather events (Huai 2016, Pandey *et al* 2017). To fully understand the sustainability of charcoal producer livelihoods and, in particular, their resilience to shocks, further studies are warranted that go beyond our static assessment of synergies and trade-offs towards an assessment of their temporal dynamics.

Our results indicate that livelihood capitals of charcoal producers are generally higher in CB-villages than OA-villages. Yet, the clear separation observed in Fig. 6a between CB-villages and OA-villages indicates that the increase in livelihood capitals in CB-villages occurs at the expense of income per bag, for reasons explained in Section 4.1. Fig. 3 and 4 reveal that charcoal producers operating in CB-villages may compensate for the reduced income per bag by producing more bags per kiln, so that they obtain similar income per year from charcoal as producers in OA-villages. To acquire these bags, producers in CB-villages may cut more trees than those in OA-villages, which could ultimately threaten the sustainability of forest use if production is not in line with the harvesting plan. Forest monitoring funded through taxes derived from charcoal production should largely prevent this. Nevertheless, anecdotal information from our study area suggests that charcoal producers in CB-villages do not fully comply with the harvesting plan because charcoal production to a large extent occurs outside designated areas (unpublished results). Potential mismatches between the implemented harvesting plan and reality may partially result from the lower income per bag in CB-villages because this may tempt them to produce more charcoal than prescribed to sustain their livelihoods or to produce outside of the CBNRM scheme to avoid taxes. Additionally, a recent study found that designated areas for forest use are often too small to satisfy local wood demands (Treue *et al* 2014). Tax avoidance as a consequence of a discrepancy between direct financial benefits under legal versus illegal forest use has been observed in previous studies on CBNRM of forests (Ameha *et al* 2014, Mohammed and Inoue 2012a, Richards *et al* 2003). However, higher production rates in CB-villages than OA-villages may also have non-financial reasons and are not necessary indicative of illegal activities. For example, higher social capital in CB-villages than in OA-villages may increase charcoal production per year because collaboration allows charcoal producers to build larger kilns that provide more charcoal bags; a process we find significant evidence for in two CB-villages. Besides this, qualitative data reveals that charcoal producers from OA-villages are interested to join associations to create larger kilns.

#### *4.2.1 Synergies and trade-offs between livelihood capitals under CBNRM*

In CB-villages, we find synergies between social capital and natural capital, which suggests that support from others and formalization of interactions through training schemes and participatory forestry may foster sustainable forest use. This corroborates recent findings that cooperation among users of the natural resource enhances the adoption of conservation strategies because it reduces free-riding behavior among users, especially under collective choice rules (Nie 2018). The strong synergy between past and present forest sustainability reveals that charcoal producers in CB-villages perceive that their forest has been sustainably used in the past and will be sustainably used in the future. This finding implies the success of the TTCS project in mobilizing charcoal producers, other forest users and the entire community (because of community development benefits) to become stewards of their village forest. Interestingly, feelings of support from others synergizes with housing quality, charcoal bags per kiln and income per bag, revealing that social capital in the form of support from fellow villagers and governance agencies may aid charcoal producers in obtaining income, potentially allowing them to invest this income in physical assets, such as housing. This positive correlation between social and financial capitals is corroborated by literature that shows enhanced household income with access to social capital (Narayan and Pritchett 1999, Shen and Bian 2018). Yet, financial capital could also increase social capital because income equality may promote social capital, highlighting that relationships between social and financial capital are complex and should be explored further (Paarlberg *et al* 2018). The synergy between charcoal bags per kiln and production efficiency in CB-villages indicates that some producers produce more efficiently than others. These results suggest that high technical knowledge about charcoal production does not promote efficiency, despite high levels of collaboration in CB-villages that should theoretically foster increased knowledge exchange. This finding contrasts with literature that shows positive correlations between social and human capital (Büchel and Duncan 1998, Israel *et al* 2001, Teachman *et al* 1997), and highlights opportunities in improving current participatory charcoal production schemes to ensure knowledge and skills transfer between charcoal producers.

We also find trade-offs between livelihood capitals in CB-villages, namely between charcoal production skills resulting in efficient production and knowledge about forest, as well as health care. The negative correlation between income per bag and health risk awareness reveals a tradeoff between production practices that protect health and efficient production that results in high quality charcoal that provides high income. Charcoal production may result in respiratory problems (Kato *et al* 2004, de Souza *et al* 2020), and physical injuries (Tiamiyu *et al* 2021). Our qualitative data indicate that charcoal producers suffer from many injuries related to charcoal production, including cuts from machetes and falling branches, and even reported death from falling into a kiln or through a falling tree. Future studies may investigate ways in which charcoal producers can both safely and efficiently produce charcoal to mitigate these health risks. Interestingly, we observe a trade-off between production efficiency and production experience in CB-villages, which contrasts with literature that highlights the importance of experience to acquire efficient production skills (Schure *et al* 2019). The majority of young producers in CB-villages indicated that they only recently obtained charcoal production skills through the CBNRM training scheme. This finding may indicate that efficient charcoal production techniques can be taught effectively to new producers, allowing them to more efficiently produce charcoal than experienced producers, who have not received training or stick to their practices. This highlights opportunities for schemes that promote active knowledge sharing about efficient charcoal production practices to widely increase production efficiency. Finally, trade-offs between forest impact awareness and production efficiency indicate that charcoal producers do not require knowledge of the impact charcoal production has on forests to efficiently produce charcoal. This may suggests a need for increased attention to forest ecology and sustainability in training sessions to reconcile production efficiency and sustainable forest use.

#### *4.2.2 Synergies and trade-offs between livelihood capitals under open access*

In OA-villages, we observe synergies between distance to forests and interaction formality. This may indicate that charcoal producers who live in the village center and far from forests have the opportunity to become members of associations, while charcoal producers living in more rural areas closer to forests do not. This finding reveals challenges in the promotion of formalized interactions between charcoal producers in sparsely populated areas. It is important to formalize interactions because we show that collaboration may enhance access to financial capital and housing. Besides this, previous studies show that collaboration can increase natural capital through enhanced adoption of conservation practices (Nie 2018). In OA-villages, we also find synergies between financial capital, health risk awareness and faced health risks. This result may reveal connections between the magnitude of charcoal production, the types of trees utilized and the health risks charcoal producers face in OA-villages. For instance, charcoal producers may face larger health risks when constructing a large kiln, when cutting large trees, and when burning a large pile of wood, than when creating small kilns fueled by small trees or shrubs. Interestingly, we find a positive association between access to tools and enhanced cooperation, knowledge, income and perceived sustainability. With more (and better) tools, charcoal producers may be able to fell larger trees together. Additionally, the use of tools requires knowledge about charcoal production and forests. Access to tools may also increase income, as some charcoal producers in OA-villages mention that the use of chainsaws allows them to cut larger trees with solid cores, which produce high quality charcoal (Adeniji *et al* 2015, Oduor *et al* 2012).

We find trade-offs between health risk awareness, production efficiency and cooperation with others in OA-villages, which echo findings for CB-villages. These trade-offs further indicate that awareness of health risks may cause charcoal producers to produce more carefully, which may result in reduced charcoal production efficiency. In contrast to CB-villages, low cooperation with others in OA-villages may impede knowledge exchange about health risk mitigation. Interestingly, access to housing shows negative associations with both income per bag and access to tools, suggesting that producers who construct a high number of houses may not need to produce as much charcoal as producers with a lower number of houses, potentially because they are wealthier in terms of physical assets. Trade-offs between past forest sustainability and impact awareness in OA-villages may reveal a potential threat to forest resources because charcoal producers with higher forest impact awareness are more pessimistic about the fate of their forests than producers with low forest impact awareness. Combined with an already lower perceived past and future sustainability in OA-villages than in CB-villages, this finding may reveal a loss of forests in the past, which may continue in the future. Interestingly, anecdotal information on change in aboveground biomass in OA-villages does not show overexploitation of forest resources in the village; yet, these initial results do expose hotspots of forest loss (unpublished results).

### *4.3 Lessons learned*

It is important to acknowledge the limitations to the results of this study. First, our surveys took about two hours to complete, which likely influenced the concentration of the interviewees and their willingness to explain their answers (Burchell and Marsh 1992). Second, interviewers faced delays because (i) village leaders faced challenges in informing interviewees prior to interviews, (ii) there were misunderstandings by village leaders about sampling procedures, and (iii) long and difficult travelling conditions to interviewees delayed the starting time of interviews. Third, interviewers needed to actively explain some survey questions to charcoal producers, which may have caused deviations in the interpretation of these questions. For example, we asked charcoal producers about the distance they traveled to the forest in kilometers but this metric was not custom in the villages. Therefore, charcoal producers either provided their travel time or indicated the distance in terms of the number of football fields one kilometer entails. Additionally, some survey questions were difficult to answer for producers. For instance, many producers in OA-villages were unable to provide the number of kilns they created per year, often indicating that they only produce charcoal when needed. Cultural norms may also have influenced answers, e.g., charcoal producers who only produce sporadically may have felt that their charcoal production practices are negligible, causing them to refrain from answering questions related to charcoal production. Unfortunately, we were unable to schedule abundant time to test surveys at the time of study because the first and last author of this study were unable to travel to Tanzania to conduct fieldwork, challenging cooperative adjustments of surveys in the field. Yet, we were able to include twelve or more charcoal producers per village, which produces sufficient variation for statistical comparison and two days of survey testing took place. Fourth, charcoal producers in OA-villages may have hesitated to take part in our survey because of the illegality of their practice. However, although charcoal producers in OA-villages were initially more hesitant to participate in the study, more producers volunteered after the first interviews were finalized, indicating that the questions were not perceived as threatening. Nevertheless, fewer charcoal producers were interviewed in OA-villages because Village Councils had restricted knowledge about charcoal production activities in their village and because of Covid-19. Finally, wealth was partly determined based on housing quality, making this a potentially circular indicator in our assessment of the impacts of wealth status on livelihoods. However, because we do not observe a correlation between wealth status and physical capital, it appears that this indicator does not influence our results.

It is important to acknowledge the limitations to the approach if this study. First, the sample sizes differed per indicator for the different analyses because interviewed charcoal producers did not provide an answer to at least one of the questions on the survey. We carefully presented these numbers so that the sample size can be taken into consideration when interpreting our results (see Appendix Table A1). Second, when combining answers into indicators, we made several assumptions. When charcoal producers answered only some of the questions used to inform an indicator that relied on summing survey answers, we still included the results. This, because we wished to include as much information as possible to better understand charcoal producer livelihoods and the effect of governance on them, even though large variations in answers to answer certain questions due to missing data may have overshadowed potential effects of governance and could have weakened observed tradeoffs and synergies. Missing data may partly explain the limited correlations between, the large variation in and the small differences between human capital indicators across villages because charcoal producers mainly refrained from answering some of the questions integrated in these indicators. Besides this, charcoal producers sometimes provided answers as ranges, e.g., the income per bag could range between 8000 and 10,000 TZS depending on the season. In this case, we consistently used the largest value mentioned by the interviewee, which may have led to an overestimation of the total annual income derived from charcoal production. Third, charcoal producers were interviewed voluntarily and only represented part of the charcoal producer population of the village. Hence, including more charcoal producers in our sample could have produced different outcomes, as is the case for all studies relying on sampling. Fourth, other third party projects could have influenced our results; an effect we largely avoided by selecting those study villages recommended to us by TFCG because no prior project was in place concerning forest use or protection. Finally, the SLA is contested (Levine 2014). For instance, critiques state that more capitals are needed to provide for sustainable livelihoods, such as cultural (Throsby 2003) and political capital (Nee and Opper 2010). We decided not to include these capitals to limit the length of our already lengthy survey and because we expected them to be less instrumental for charcoal producer livelihood sustainability than those assessed in this study. Nevertheless, our study did address one of the main critiques on the SLA; a lack of discussion of livelihoods in relation to governance (Scoones 2009). We assessed effects of formal governance because large investments are made in the negotiation, construction and enforcement of decisions regarding forest use and conservation by many tropical countries and third parties around the world in order to mitigate forest degradation and deforestation (van 't Veen *et al* 2022). Yet, we recognize that informal forest governance (i.e., societal norms) may influence livelihoods in parallel and may have affected the success of formal governance (Ashu 2016, Pacheco *et al* 2008, Osei-Tutu *et al* 2015).

## 5. Conclusion

Worldwide, charcoal production causes forest degradation and 7% of deforestation, while simultaneously providing energy for hundreds of millions and income for over 40 million people. This trade-off between forests and livelihoods may be reconciled through governance that simultaneously considers social and environmental goals in charcoal production systems. Here, we present a first examination of governance effects on trade-offs and synergies between livelihood capitals of charcoal producers in governance regimes that provide open access to forest resources and governance regimes that enable communities to manage their forest collectively (CBNRM). Our results highlight opportunities to foster sustainable livelihoods by initiating governance transitions to CBNRM because this enhances access to multiple livelihood capitals, including natural, social and to a certain extent human capital. This rise in livelihood capitals under CBNRM is due to a revenue-sharing scheme under which taxes derived from charcoal production are put in a community fund that is invested in forest management and community development projects, which promote social and natural capital at individual charcoal producer level and physical capital at community level. In other words, some of the financial capital of individual charcoal producers is transformed into other types of capital that benefit both charcoal producers and the community they are part of. Despite the livelihood benefits, we find a trade-off between financial capital and other capitals, which may threaten charcoal producer livelihoods, since producers may not be able to obtain enough income to sustain their livelihoods and/or may quite charcoal production. This has implications for revenue-sharing and ultimately may jeopardize forest management and community development. This result reveals the importance of identifying trade-offs between livelihoods capitals when fostering and expanding governance transitions to make appropriate adjustments to existing policies. For instance, the trade-off between income per bag and other livelihood capitals reveals the need to foster large scale governance transitions to reduce competition between those areas where prices for forest products are lower due to tax evasion, and those areas where prices are higher as a result of tax collection. If further governance transitions from open access to CBNRM are enacted, policy makers and practitioners could explore ways in which such CBNRM schemes may be up-scaled without interference of an external party. Such widespread transitions would benefit entire communities on the long term, by assuring continued availability of forest resources that foster diverse livelihoods.

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**Data statement**
Anonymized survey data is available upon request.

## Author contributions

The author contributions are based on CRediT (Contributor Roles Taxonomy), which aims to recognize individual author contributions to facilitate collaborations and to diminish disputes among authors (https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement).

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# Chapter 8

## Forest governance and development effects on tropical charcoal production and deforestation

**Authors**

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Although **Chapter 3** to **Chapter 7** provide important insights into the impact of transitions in charcoal production systems, their focus is on resource systems at a local scale (village scale / village size modelling environment), including local users, resource units and governance systems. These resource systems are affected by local social, economic and political settings and governance systems. However, charcoal is produced in almost all tropical countries in the world (FAO 2017). On the global scale, charcoal production is affected by county-specific social, economic and political settings (Nyembe 2011), as well as the forest governance systems put in place by national governments (Schure *et al* 2013), each with their own quality of governance (Sulaiman *et al* 2017).

In **Chapter 8**, I provide a global context for the local findings of **Chapter 4** to **Chapter 7**, by providing an overview of the effects of forest governance (quality) and economic settings on charcoal production and deforestation in 54 tropical countries. Hereby, I provide insights into the importance of the governance system unit of the social-ecological system and its relation to countries' economic settings.

**Figure 8.1** provides an overview of the social-ecological system components assessed in **Chapter 8**, their interactions, and the specific charcoal production systems compared. The **Supplementary Materials** of **Chapter 8** can be found in the **Appendix of Chapter 8** of this thesis.

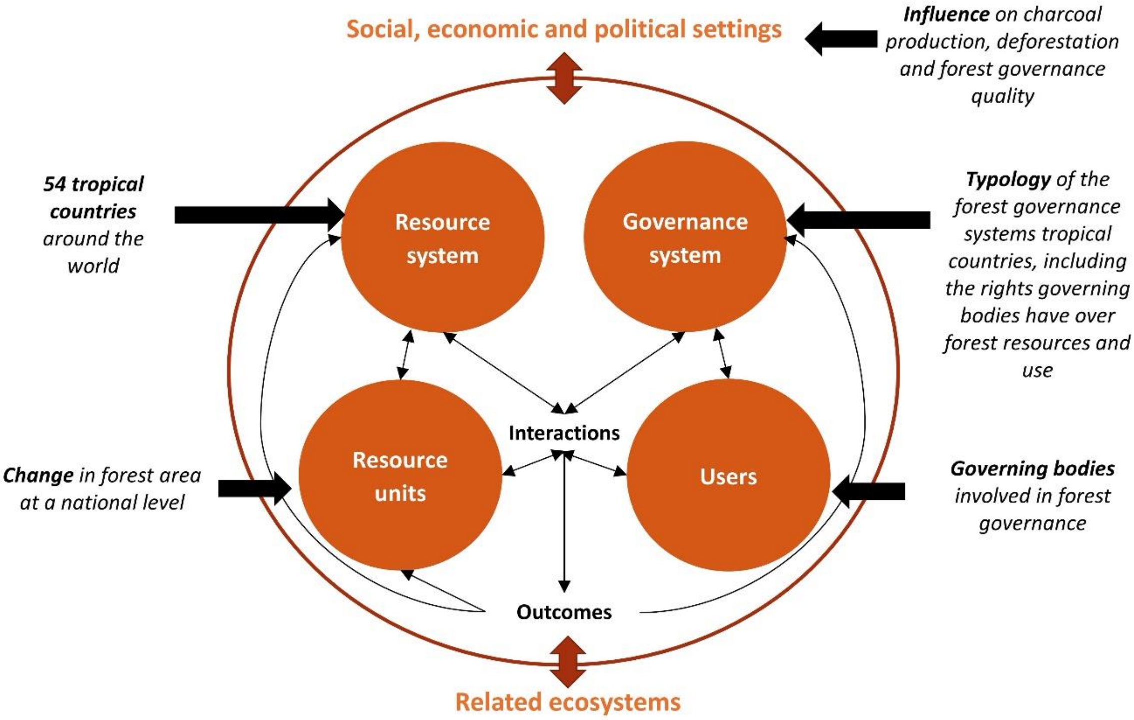

**Figure 8.1.** The social-ecological system components assessed in **Chapter 8**, their interactions, and the specific charcoal production systems compared.

Published scientific paper

# Forest governance and development effects on tropical charcoal production and deforestation

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## Abstract

Severe loss and degradation of tropical forests affects ecosystem services and livelihoods. Charcoal, an important energy and income source for millions of people, causes 7% of tropical deforestation and forest degradation. Forest governance aims at managing forest-related issues. On the one hand, development allows for financial investments in forest governance, e.g., in monitoring and enforcement, with the aim to control deforestation. On the other hand, deforestation often continues with increased human wellbeing. Here, we aim to (i) globally examine effects of forest governance on charcoal production and deforestation, and (ii) understand its association with development. We developed a typology of tropical forest governance systems based on a literature review of 54 USAID Country Profiles and combined it with global data on charcoal production, deforestation, governance quality and development. Our results suggest that countries’ development status affects charcoal production rather than governance quality; we observe a negative relationship between development status and charcoal production per capita (HDI: $F_{(1,50)} = 4.85$, $p = 0.032$; GNI: $F_{(1,50)} = 4.64$, $p = 0.036$). The limited influence of governance quality and rights on charcoal production per capita and deforestation suggests mismatches between formal and informal governance and exposes challenges in top-down percolation of governance goals. Our results highlight potential importance of tenure rights and potential opportunities for regional governing bodies to bridge local formal and informal actors to improve forest governance. Positive effects of regional tenure are driven by mixed effects of high development and governance quality related to decentralization in Asia and South America, highlighting transitions from charcoal as livelihood energy source to global commodity. Variability in results for FAO and UN charcoal production data advocates for better monitoring programs. Yet, for the first time, we explore global interactive patterns in charcoal production, development and governance – a starting point to differentiate good governance.

**Keywords:** Charcoal, forest products, tropics, governance, natural resource management

## 1. Introduction

Severe loss of forests (Curtis *et al* 2018) affects the supply of ecosystem services, such as woody biomass production, and biodiversity (Miles and Kapos 2008), and livelihoods depending on them (Carrasco *et al* 2017). Compared to temperate forests, tropical forests face largest risks of deforestation and forest degradation (Sloan and Sayer 2015). Forest governance aims to limit deforestation and forest degradation through formal and informal institutions (laws, rules and norms) of public and private governing bodies (e.g., governments, private companies and indigenous organizations), which negotiate, make and enforce binding decisions about management, use and conservation of forest resources (FAO Program on Forests 2011). Impacts of forest governance on forest use and conservation are variable (Persha and Andersson 2014), despite continuous efforts to enhance its quality and effectiveness (Arts *et al* 2010, Biermann and Pattberg 2008). Financial investments are necessary to uphold quality forest governance, such as investments in institutional development or monitoring and enforcement by governing bodies (FAO Program on Forests 2011, Köthke 2014). Therefore, forest governance quality is expected to positively relate to development status (i.e., a country's quality of life and economic wellbeing), because it allows for investments in forest governance (Asongu and Jingwa 2012, Houballah *et al* 2020), and other societal assets, such as education (Lin 2004) and infrastructure (Fan *et al* 2016), which can affect governance quality. Yet, research indicates that deforestation often continues with increased human wellbeing (Delabre *et al* 2020, Jha and Bawa 2006). Therefore, a better empirical understanding of the relation between forest governance characteristics and forest use and protection (Arts and Vissen-Hamakers 2012, Biermann and Pattberg 2008), and its association with development is needed (Beauchamp *et al* 2020).

In the majority of tropical countries a formal forest governance system has been implemented (Fischer *et al* 2020). Across the tropics varying forest governance systems exist, ranging from centralized, to regionalized and decentralized systems, varying across continents (Arts and Vissen-Hamakers 2012). Multiple governance systems may co-occur and change over time due to new and changing policies (Arts *et al* 2010, Schreckenberg and Luttrell 2009), strongly influenced by colonial history and governance in other nations (Becker 2001, Mwangi 1998, Tucker 1982, von Hellermann 2013). For example, many centralized governance systems were replaced by decentralized ones over the past decades, as it has been shown that local or regional institutions and a distribution of responsibilities results in better governance outcomes (Arts *et al* 2010, Arts and Vissen-Hamakers 2012). Decentralization is thought to produce better outcomes because it relies on participation of multiple governing bodies, believed to foster political accountability and more responsive governments, theoretically resulting in both accountable and effective governance (Rondinelli *et al* 1983). Yet, variable outcomes for forest use and conservation are observed across decentralized governance systems (Larson and Petkova 2011), likely because they contain a large diversity of governing bodies, which differ in the tasks they have and the way they collaborate with each other (Andersson *et al* 2014).

Generally, all governance systems explicitly define formal institutions in binding policy and legal documents, e.g., forest acts (FAO Program on Forests 2011). For example, governments outline governing bodies with the right of forest tenure, which, if secure, play an important role in the adoption and implementation of sustainable forestry (Arnot *et al* 2011). Simultaneously, informal institutions, i.e., societal norms, may complement or defy formal ones (Pacheco *et al* 2008). In the majority of tropical countries, the forestry sector is still informally governed, as formal governing bodies may have limited resources and capacity to implement formal governance, resulting in the persistence of illegal forest use (Ashu 2016, Osei-Tutu *et al* 2015, Pacheco *et al* 2008). Effective incorporation of informal institutions may foster higher forest governance quality (Osei-Tutu *et al* 2015, Yeboah-Assiamah *et al* 2017). However, the extent of informal forest governance and its effects on forest use and conservation remains unclear (FAO and UNEP 2020), although evidence from local studies suggests that informal governance through self-organization can foster more effective governance than formalized governance systems in certain occasions (Andersson *et al* 2014).

Institutions implemented by governing bodies are not singular but vary depending on forest tenure, involved governing bodies (Kohler and Schmithusen 2002), forest products extracted (Brobbey *et al* 2015), and whether products are used for self-sustaining or commercial purposes (Ribot, 2001). Charcoal is arguably among the least examined forest products, despite being an important energy and income source for hundreds of millions of people in the tropics (FAO 2017). Charcoal production is an important cause of forest degradation (Sedano *et al* 2016), and is responsible for up to 7% of annual deforestation globally, especially under ineffective governance scenarios without investment in post-harvesting management (Chidumayo and Gumbo 2013). Overall, charcoal production is projected to increase with 5% by 2100, likely causing further deforestation and forest degradation (Santos *et al* 2017). Effective forest governance that incorporates energy substitution options to reduce demand (van 't Veen et al 2021) is required to mitigate these negative effects (Schure et al 2013), besides routine monitoring and enforcement to control access and forest use.

In many tropical countries, forest governance already aims at controlling charcoal production (Schure *et al* 2013), indicating that charcoal production should in theory be influenced by countries' formal governance systems (Laan *et al* 2010). Formal forest governance intends to foster sustainable use and conservation of forests, a practice that requires substantial financial investments and the efforts of many governing bodies involved (Fischer *et al* 2020). The manner in which formal forest governance aims to achieve this is documented (USAID 2014) and its quality is quantified (Kaufmann *et al* 2010), allowing for an assessment of its eventual impact on forest use and conservation. Therefore, it is important to study formal governance (Larson *et al* 2008, Schure *et al* 2013), especially when formal and informal governance are antagonizing (Goetter 2019). Besides investments in routine forest governance interventions, other investments have been made in efficient cooking stoves and alternative energy and income sources for communities (Cotton *et al* 2021, Zulu and Richardson 2013) to foster energy transitions with the aim to reduce charcoal demands (Santos *et al* 2017, van 't Veen *et al* 2021). The size of such investments relates to tropical countries' access to financial resources to fund them (Laan *et al* 2010). Besides this, higher financial means may provide incentives for urban consumers to shift to alternative energies (e.g., gas), as observed in South American and Asian countries (FAO 2017). This indicates a likely effect of development status on charcoal production and (related) deforestation in tropical countries (Schure *et al* 2013).

In this study, we aim to (i) examine effects of formal forest governance on charcoal production and subsequent deforestation, and (ii) understand its association with development. We hypothesize that formal forest governance has limited effect on charcoal production and deforestation because of a lack of resources to finance effective governance and because of a potentially important role of informal governance. Furthermore, we expect that decentralized governance and tenure rights foster higher governance quality and provide better outcomes for charcoal production than centralized governance systems. Finally, we expect lower charcoal production and deforestation in countries with higher development status because financial resources should enable higher quality governance, access to alternative energies on the demand side, and alternative incomes on the supply side in rural areas, as often other activities than charcoal production are adopted with enhanced wellbeing (FAO 2017). Hence, we expect continental patterns, with high development and low charcoal production in Asia and South America and low development and high charcoal production in Africa (FAO 2017).

## 2. Methodology

### *2.1 Study system and typology of forest governance*

Our study system consists of 54 tropical countries and their forest governance systems. We defined a typology of formal forest governance systems by identifying scales at which governing bodies operate and the rights they have over forest resources. In the typology we recognize that forest governance is a nested process in which multiple governing bodies have a range of overlapping rights (Agrawal *et al* 2008, Arts 2014, Biermann and Pattberg 2008).

We reviewed USAID country profiles on tenure rights (USAID 2013) to inform our typology (**Supplementary Materials A**). We used these profiles because they provide detailed and consistent overviews of forest governance in tropical countries (Anon 2020). Forest governance information from other sources is scattered and multi-lingual, hence challenging to utilize.

We defined four types of governing bodies: (i) national, (ii) regional, (iii) local, and (iv) individual, which operate at different scales. National governing bodies operate at national scale, e.g., ministries. Regional governing bodies are sub-national entities operating at regional level, e.g. province or State. Local governing bodies are sub-regional entities operating at the lowest communal governing level, e.g., municipalities or village governments. Finally, individual governing bodies are individual people and companies operating locally on forest land or trees over which they have rights. In the case of regional governing bodies, there may be multiple nested bodies in one country, such as provincial and district governments. Individual governing bodies do not include actors further up the charcoal value chain, like wholesalers, because they lack direct rights over forests.

We defined two main rights governing bodies may have in forest governance systems: (i) enforcement, and (ii) tenure. Enforcement is the formal right to enforce (by-) laws on forest use and protection. Tenure is the formal right to tend forest land or trees, like ownership and lease rights. Governing bodies may have multiple rights at once or may not have specific rights. We specifically focused on formal rights of enforcement and tenure because they are specified by countries' forests acts (USAID 2013), and can influence forest governance outcomes (Robinson *et al* 2014a). We only included governing bodies operating in the statutory domain, not those operating informally (e.g., traditional local leadership that is not formally acknowledged in existing forest acts). However, we acknowledge that in many cases, especially in most African countries, informal institutions tend to be powerful and may prevail over the formal ones (Larson *et al* 2008). This explains the mismatch between formal distribution of tenure rights and actual rights of governing bodies later described in Section 4.2 of the discussion.

We recognize that other factors beyond enforcement and tenure may influence forest governance effects on charcoal production and deforestation, e.g., market-oriented certification schemes and NGO projects (Agrawal *et al* 2008), potentially affecting deforestation (Bare *et al* 2015). Additionally, charcoal is exported to other countries and trade is increasing (Proskurina *et al* 2019). We also acknowledge that tenure right distribution does not equal the security of those rights (Robinson *et al* 2014a). Tenure security affects conservation more than the distribution of tenure rights alone (Robinson *et al* 2011). Hence, assessments of the effects of tenure rights on forest governance, charcoal production, and deforestation may indicate issues of tenure security, rather than the effect of tenure right distribution as dictated in formal forest acts.

We calculated governance richness – an indicator of polycentricity – for the entire governance system, and for tenure and enforcement rights per country by summing the number of governing bodies involved. We used the typology of governance systems and governance richness indicators derived from it to assess effects of inclusion of specific types governing bodies (e.g., regional bodies) and governance composition on charcoal production, deforestation, forest governance quality and development.

### *2.2 Data collection*

We used data on charcoal production and consumption from United Nations (UN - 2018) (http://data.un.org/Data.aspx?d=EDATA&f=cmID%3ACH), and charcoal production data from the Food and Agriculture Organization (FAO - 2017) (http://faostat.fao.org). The first was collected through the UN Energy Statistics Questionnaire (UN 2017). The second was gathered through an annual survey by the FAO Forestry Division and estimated using trade journal reports, statistical yearbooks and other sources. Charcoal production data from both the UN and FAO correlated well ($R^2 = 0.53$, $F_{(1,52)} = 61.4$, $P = 2.3x10^{-10}$) (**Supplementary Materials figure B1**), but charcoal production varied per country between the two data sources ranging from 0 to 2,197,000 Mg.

We obtained data on total population per country (2018) from the World Bank (https://data.worldbank.org/indicator/SP.POP.TOTL). We used it to calculate charcoal production per capita for both UN and FAO data; these are relative measures of charcoal production. We assessed charcoal production per capita because formal governance affects rural charcoal producers, urban consumers, transporters and wholesalers (e.g., through permits for production, transportation or sale) (Schure *et al* 2013), while subsidies for alternative energies and efficient cooking stoves mainly influence urban consumers (Mwampamba *et al* 2013). We used data on total forest land per country (x1000 ha) of 2017 and 2018 from FAO (http://faostat.fao.org). To calculate deforestation we subtracted forest land of 2017 from that of 2018, multiplied it by -1 and divided it by the total forest land of 2018 to derive relative values of deforestation and afforestation. In our deforestation index, deforestation is positive and afforestation negative. See the Global Forest Resource Assessment (http://www.fao.org/forest-resources-assessment/background/en/) for more information. We divided net forest conversion by total forest area per country to calculate deforestation, providing a relative measure of forest change.

We used governance quality data from the Worldwide Governance Indicators (WGI - 2017) (https://info.worldbank.org/governance/wgi/), which reflect conditions under which forest governance operates (Afawubo and Noglo 2019, Umemiya *et al* 2010). We expect that governance quality influences the effectiveness of forest governance to control charcoal production and (related) deforestation. The data includes information on (i) Voice and Accountability, (ii) Political Stability and Absence of Violence, (iii) Government Effectiveness, (iv) Regulatory Quality, (v) Rule of Law and (vi) Control of Corruption indicators (see Kaufmann et al., 2010 for indicator definitions). Unfortunately no global data on informal governance nor on its quality were available at the time of study. As indicators for development, we included Gross National Income (GNI - 2017)) and the Human Development Index (HDI - 2017). We obtained GNI from World Bank (https://data.worldbank.org/indicator/NY.GNP.MKTP.CD), and we obtained HDI from the United Nations Development Program (http://hdr.undp.org/en/content/human-development-index-hdi). **Table 1** explains rationales for the inclusion of governance quality and development indicators.

For all datasets, we downloaded the most recently available data at the time of study.

### *2.3 Data analyses*

First, we calculated pair-wise Spearman rank ($\rho$) correlations (Zar 1972) between (i) charcoal production per capita (FAO, UN), (ii) deforestation, (iii) governance quality, (iv) governance richness, and (v) development. We used linear regression to assess relationships between the indicators for which normality could be achieved. We used transformations to achieve normality, namely, we square-root transformed charcoal production per capita (UN), deforestation, and all governance quality indicators, and we log-transformed GNI. Finally, we conducted a Principal Component Analysis (PCA), which is a method that identifies the number of orthogonal (i.e., independent) dimensions in any given data set. This method is commonly used to reduce dimensionality in large datasets, i.e., by identifying axes where the original variables are combined, hereby minimizing loss of information (Wold *et al* 1987). The PCA conducted in this study included the variables charcoal production per capita, deforestation, governance quality, governance richness, HDI and GNI. First, we scaled the variables included in the PCA, to assure each variable contributes equally to the analysis, using the “scale” function of the R-package “base”. Second, we computed a covariance matrix to differentiate relationships between all variables. Third, we computed eigenvalues and eigenvectors of the covariance matrix, which correspond to the principle components that explain the maximal amount of variance in the data, with the first principle component containing the maximal information, followed by the second and so on (Abdi and Williams 2010, Wold *et al* 1987). We calculated factor loadings, where a factor (or principle component) is a combination of variables and the loadings reflect the extent to which variables are related to that factor (Yong and Pearce 2013).

**Table 1.** Rationale for including World Governance Indicators (WGI) from the World Bank, the Human Development Index (HDI), and Gross National Income (GNI) to assess the effect of governance quality and development on charcoal production and deforestation.

| **Indicator** | **Rationale for inclusion in this analysis** |
|---|---|
| *Corruption control (GQ_Cor)* | Corruption occurs when laws, rules and regulations are not respected, including those on forest use, which may affect deforestation in multiple countries (Koyuncu and Yilmaz 2009, Galinato and Galinato 2011). |
| *Rule of Law (GQ_RoL)* | Rule of law influences the enforcement of property rights and ownership of land by governing bodies, which affects the way forests are used and laws, rules and regulations of forest governance systems are obliged to (Deacon 1994). Rule of law may both influence deforestation levels (Umemiya *et al* 2010), and increase likelihoods of a forest transition (Barbier and Tesfaw 2015). |
| *Regulatory quality (GQ_RQ)* | Markets are thought to rely on reliable forest policies that permit and promote private sector development (i.e., regulatory quality) to assure a return of investment (Pedroni *et al* 2009), hereby providing incentives to protect the forest (Barbier and Tesfaw 2015), which may reduce deforestation at a global scale (Umemiya *et al* 2010). However, better access to markets can also increase deforestation because certain policies enhance access to forests (e.g., providing infrastructure to access forests) or promote land clearing (Barbier and Tesfaw 2015). Overall, it depends on which forest polices are implemented to promote private sector development and whether they aim to limit deforestation (Barbier and Tesfaw 2015). |
| *Political stability (GQ_PS)* | Political instability may incite enhanced forest exploitation because of a lack of control over forest resources and insecure property rights (Deacon 1994, McCarthy and Tacconi 2011), or because specific units, such as rebel groups, actively profit from the sale of forest products, such as charcoal (Mapesa *et al* 2013). It may, however, also halt forest exploitation, e.g., because of a reduced conversion of forest land for agriculture (Galinato and Galinato 2013). |
| *Government effectiveness (GQ_Eff)* | Effective implementation of policies and public services for the use and protection of forests may reduce deforestation (Umemiya *et al* 2010, Afawubo and Noglo 2019). However, effective implementation of policies that disregard forest protection may give rise to deforestation (Jha and Bawa 2006). |
| *Voice and accountability (GQ_VaA)* | When voice and accountability is high, people are allowed to speak up to influence decision making, which is an indicator of decentralized democratic governance (Wright *et al* 2016). Decentralized governance systems in which local users actively engage with local governing bodies have a more stable forest cover (Wright *et al* 2016). However, enhanced decentralization and means to speak up may also increases conflicts (e.g., conflicts over land rights), which could enhance deforestation, despite opportunities to engage in forest management (Yasmi *et al* 2009). |
| *Human Development Index (HDI)* | Human development may negatively influence deforestation, even at high population growth (Jha and Bawa 2006). However, policy choices that disregard forest protection may inhibit the positive influences of human development on forest cover (Jha and Bawa 2006). |
| *Gross National Income (GNI)* | Forest-income curves may be U-shaped, with an initial increase in deforestation upon a rise in income because people initially have more means to exploit forests and convert forest land, until a tipping point is reached and forest exploitation reduces due to a transition to other sources of income, resources and intensified agriculture (Galinato and Galinato 2011). Besides this, national debt may lead to increased pressure on forests to relieve debt on the short term (Kahn and McDonald 1995). |

Second, we assessed potential effects of forest governance characteristics on (i) charcoal production per capita, (ii) deforestation, (iii) governance quality, (iv) governance richness, (v) development, and (vi) countries' continental origin. Because of the nested structure of forest governance systems and limited sample size, we could not distinguish influences of specific governing bodies or specific combinations of governance bodies on the response variables. Hence, we color coded governance systems by the governing bodies involved in our PCAs, to examine potential associations.

All analyses were conducted in R (Team 2019).

## 3. Results

### 3.1. Tropical forest governance typologies

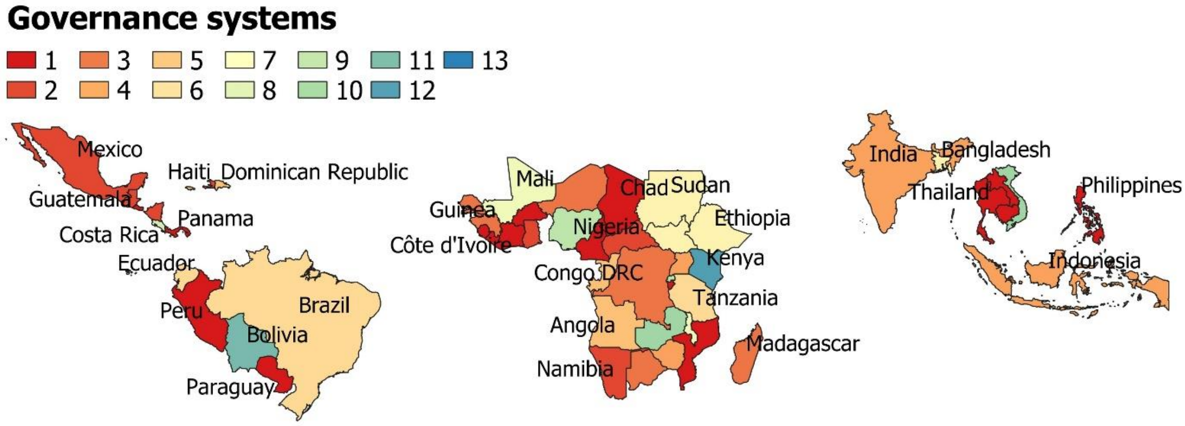

**Figure 1.** Geographical distribution of the governance systems of tropical countries around the world. The numbering is based on the governance typology visualized in **Appendix A**. No clear geographical pattern was found.

Globally, we distinguished 13 typologies for forest governance systems (see **Supplementary Materials A** for the full typology and a visualization of it), but find no clear geographical patterns (**figure 1**).

*3.2. Impact of development and governance on charcoal production and deforestation*

**Figure 2** shows the strength and direction of Spearman correlations between charcoal production per capita, deforestation, GNI and HDI, average governance quality and governance richness. We observe a weak negative correlation between governance richness and charcoal production per capita for UN data ($\rho$ = -0.16). We also observe weak negative correlations between charcoal production per capita and government effectiveness (UN: $\rho$ = -0.13, FAO: $\rho$ = -0.31), political stability (FAO: $\rho$ = -0.26), and regulatory quality (FAO: $\rho$ = -0.25). HDI and GNI negatively correlate with charcoal production per capita for both FAO ($\rho$ = -0.68 and $\rho$ = -0.61 respectively) and UN data ($\rho$ = -0.28 and $\rho$ = -0.26 respectively). Further, negative linear relationships between UN charcoal production per capita, HDI and GNI are statistically significant but weak (HDI: $R^2 = 0.07$, $F_{(1,50)} = 4.85$, p = 0.032; GNI: $R^2 = 0.07$, $F_{(1,50)} = 4.64$, p = 0.036).

We find positive correlations between deforestation and charcoal production per capita (FAO: $\rho$ = 0.33, UN: $\rho$ = 0.25) (**figure 2**). We observe a weak negative correlation between deforestation, government effectiveness ($\rho$ = -0.30), rule of law ($\rho$ = -0.23), and corruption control ($\rho$ = -0.18). We also find weak negative correlations with HDI ($\rho$ = -0.31) and GNI ($\rho$ = -0.22). However, there were no significant linear relationships.

We find significant positive relationships between average governance quality, HDI ($R^2$ = 0.37, $F_{(1,49)}$ = 36.58, p = $1.97e^{-07}$) and GNI ($R^2$ = 0.38, $F_{(1,49)}$ = 31.95, p = $7.99e^{-07}$), and a weak negative correlation between governance richness and political stability ($\rho$ = -0.18).

The first four principal components of the PCA explain the variation in our data sufficiently, with a fit of 0.98 based on off-diagonal values, where the explained proportion of variation by the first component is 37%, the second 17%, the third 9%, and the fourth 8% (**table 2; figure 3**). Hereby, we removed the outlier Ivory Coast removed, which has a 50 times higher charcoal production per capita than the subsequent highest charcoal production per capita (Haiti). We find negative loadings for charcoal production per capita for the second component. In contrast, we find strong positive loadings for HDI and GNI for the second component. We also find strong positive loadings for governance quality indicators for the first component. Governance richness exhibits high negative loadings for the third component. We find negative loadings for deforestation for the first component.

*3.3 Impact of governance characteristics on charcoal production and deforestation*

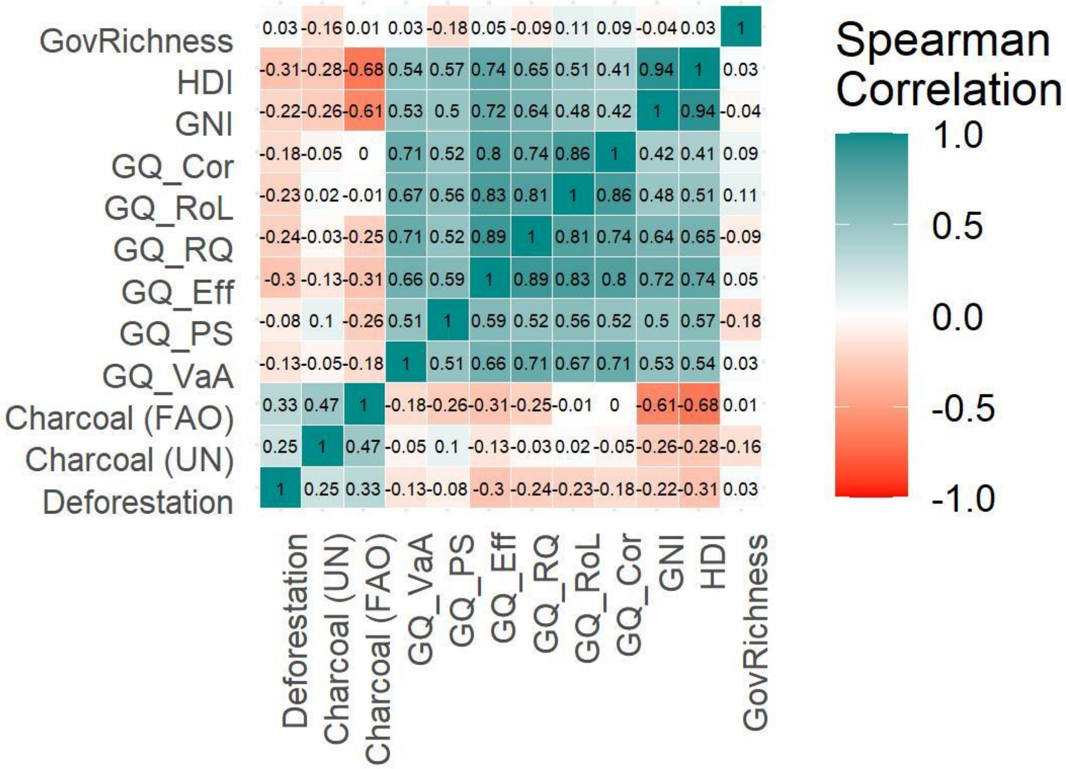

**Figure 2.** Spearman correlations between charcoal production per capita (Charcoal) for FAO and UN data, deforestation, development indicators (GNI and HDI), governance quality indicators, and governance richness. WGI governance quality indicators, included Voice and Accountability (GQ_VaA), Political Stability (GQ_PS), Government Efficiency (GQ_Eff), Regulatory Quality (GQ_RQ), Rule of Law (GQ_RoL), and Corruption control (GQ_Cor) (See Table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement.

Color-coding countries with tenure rights in the PCA reveals that regional tenure separates systems within PC2, associated with GNI and HDI and showing relatively lower charcoal production per capita (**figure 4**). Separability in PC1 is associated with local tenure, deforestation and charcoal production. Opposite relations between tenure richness and charcoal show lower charcoal production per capita for countries with more than four governing bodies involved. We do not observe separating effects of governing bodies with enforcement rights or enforcement richness. Finally, we observe that governance systems of Asian and South American countries appear separate within PC2, associated with GNI, HDI and government effectiveness, while governance systems of African countries appear separate within PC1 and associated with charcoal production per capita and deforestation (**figure 5; Supplementary Materials figure B2**).

## 4. Discussion

For the first time, we explore global patterns in charcoal production, development and governance, providing a starting point to differentiate good governance of charcoal energy

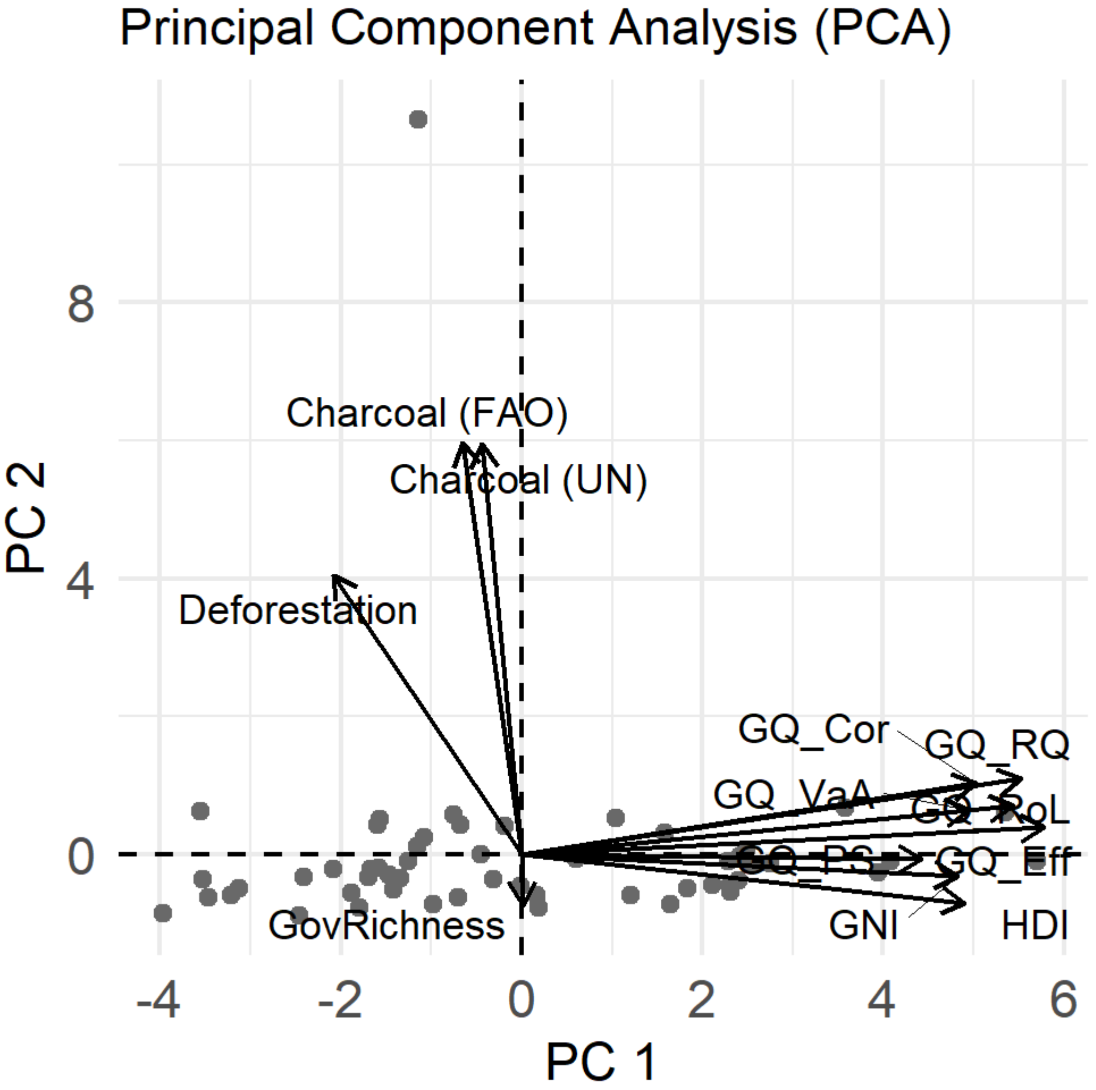

**Figure 3.** Principal Component Analysis (PCA) including charcoal production per capita (Charcoal) for FAO and UN data, deforestation, development indicators (GNI and HDI), governance quality indicators, and governance richness. WGI governance quality indicators, included Voice and Accountability (GQ_VaA), Political Stability (GQ_PS), Government Efficiency (GQ_Eff), Regulatory Quality (GQ_RQ), Rule of Law (GQ_RoL), and Corruption control (GQ_Cor) (See Table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement. The outlier that can be overserved in the upper left is Ivory Coast.

systems. Our analysis shows that charcoal production is mainly affected by a country's development status rather than its governance quality, likely brought about by a shift from charcoal as an urban energy source in African countries to charcoal as a global commodity in Asian and South American countries (FAO 2017). We find indications that several characteristics of forest governance systems, such as numbers and types of governing bodies involved influence charcoal production and deforestation.

*4.1 Impact of governance quality and development status on charcoal production and deforestation*

The low correlation between charcoal production per capita and governance quality indicators may be due to limited access to financial resources necessary to sustain high

**Table 2.** Factor loadings of the Principal Component Analysis (PCA). The outlier (i.e., Ivory Coast) is removed. Small loadings are replaced by spaces, to focus the eye on the patterns of the larger loadings. We test the hypothesis that four factors are sufficient to explain the variation in the data (i.e., the p-value should be higher than 0.05 for the model to fit) and find that four principal components explain the variation in the data sufficiently ($F_{(1,24)} = 33.53$, p = 0.09), with a fit of 0.98 based on off diagonal values.

| Variable | PC1 | PC2 | PC3 | PC4 |
|---|---|---|---|---|
| *Proportion explained by principal components* | 0.37 | 0.17 | 0.09 | 0.08 |
| *Governance richness* |  |  | 1.00 |  |
| *GNI* | 0.44 | 0.63 |  | 0.47 |
| *HDI* | 0.42 | 0.78 |  | 0.45 |
| *Corruption control (GQ_Cor)* | 0.92 |  |  |  |
| *Rule of law (GQ_RoL)* | 0.92 |  |  |  |
| *Regulatory quality (GQ_RQ)* | 0.81 | 0.32 |  |  |
| *Political stability (GQ_PS)* | 0.58 |  |  | 0.42 |
| *Government effectiveness (GQ_Eff)* | 0.89 | 0.44 |  |  |
| *Voice and accountability (GQ_VaA)* | 0.67 |  |  | 0.43 |
| *Charcoal production per capita (UN)* |  | -0.33 |  |  |
| *Charcoal production per capita (FAO)* |  | -0.71 |  |  |
| *Deforestation* | -0.30 | -0.23 |  |  |

quality forest governance through funding of (the development of) governance programs and governing bodies, such as those involved in monitoring and enforcement (FAO Program on Forests 2011, Köthke 2014, Persha and Andersson 2014), as well as to support alternative income-generating activities for communities (Cotton *et al* 2021, Zulu and Richardson 2013). Further high quality governance systems may still implement policies that disregard forest protection (Jha and Bawa 2006). Weak negative correlations between charcoal production per capita, governance effectiveness, political stability and regulatory quality, corroborate previous findings that stable nations, which formulate and uphold high quality policies and services are better equipped to govern forest use (Deacon 1994, Umemiya *et al* 2010).

Weak negative correlations between deforestation, government effectiveness, corruption control and rule of law, furthermore, corroborate findings that effectively upholding implemented policies reduces deforestation (Deacon 1994, Koyuncu and Yilmaz 2009, Umemiya *et al* 2010). This is likely caused by upholding high quality policies and services, which helps to simultaneously enhance adoption of conservation strategies and to avoid free-riding behaviors (Nie 2018). Evidence suggests that the presence of local institutions designed to match people's preferences through participatory processes further enhances effective upholding of implemented polices (Schreckenberg and Luttrell 2009). These local institutions are characteristic of the current paradigm shift towards participatory natural resources management across most tropical countries (Schreckenberg and Luttrell 2009).

The observed negative relationships between charcoal production per capita, HDI and GNI may be explained by an increased capacity of countries and citizens to invest in alternative energy resources, like gas (FAO 2017, Broto *et al* 2018, Kojima 2011), which are more costly than locally sourced charcoal (Kojima 2011). Hence, upon increased financial means transitions may occur from charcoal to alternative energy sources (Kojima 2011), and may refrain previously poor people from producing charcoal, as increased access to alternative income sources becomes available (Cotton *et al* 2021, Zulu and Richardson 2013). This is illustrated by the clear separation between African countries from Asian and South American countries (**figure 5**). These results highlight the dependency of African countries on charcoal as a livelihood energy source, and the transition to charcoal as a global commodity in Asian and South American countries (FAO 2017).

Weak negative correlations between deforestation, GNI and HDI, furthermore, corroborate observations of reduced deforestation with human development (Jha and Bawa 2006), where non-linearity may explain the weak relationship (Galinato and Galinato 2011). However, as charcoal production remains a vital livelihood diversification strategy and charcoal an accessible fuel for hundreds of millions (FAO

2017), energy transitions should carefully be anticipated (Zulu and Richardson 2013). Our study highlights countries that lead the way to higher governance quality (e.g., Botswana, Senegal, Costa Rica) and lower charcoal production and deforestation (e.g., Cameroon, Zimbabwe and Congo), which provides a starting point to identify governance that allows for continuous charcoal production without depleting forests in less wealthy countries (**Supplementary Materials figure B2**).

Significant positive relationships between forest governance, GNI and HDI agree with findings which show that HDI leads to an increase

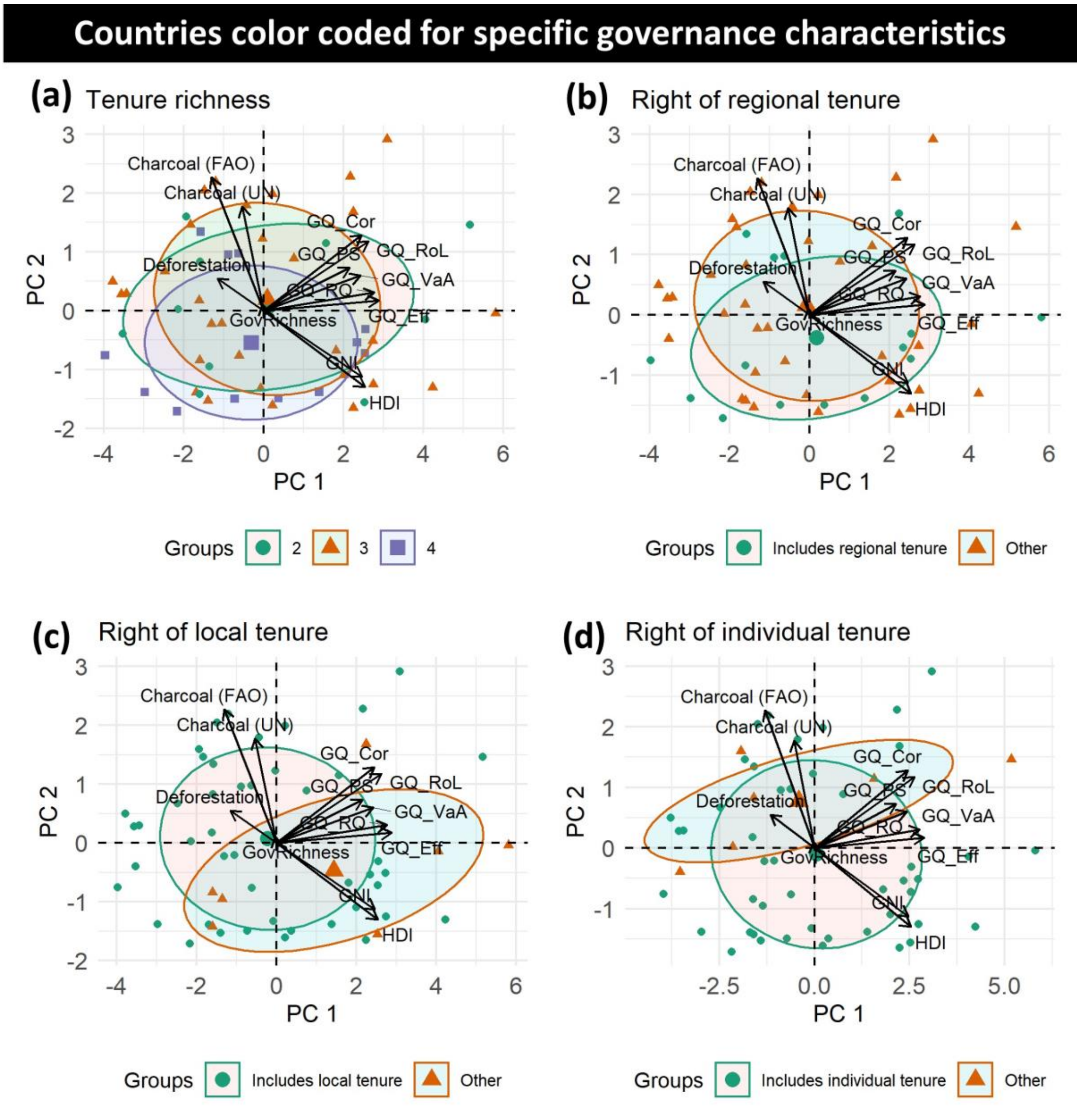

**Figure 4.** Principal Component Analysis (PCA) of figure 3, where groups highlight: (a) number of governing bodies involved in tenure (tenure richness) and whether countries provide tenure rights to (b) regional, (c) local or (d) individual governing bodies, besides other governing bodies. The PCAs include charcoal production per capita (Charcoal) for FAO and UN data, deforestation, development indicators (GNI and HDI), and governance richness. WGI governance quality indicators, included Voice and Accountability (GQ_VaA), Political Stability (GQ_PS), Government Efficiency (GQ_Eff), Regulatory Quality (GQ_RQ), Rule of Law (GQ_RoL), and Corruption control (GQ_Cor) (See Table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement. We have removed one outlier (Ivory Coast) to provide a better visualization.

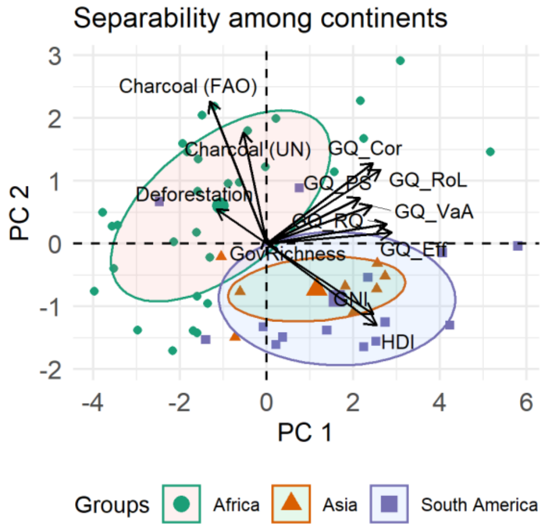

**Figure 5.** Overview figure of the same Principal Component Analysis (PCA) of figure 3. We have removed one outlier (Ivory Coast) to provide a better visualization. The countries (points) have been colored based on the continent they originate from (i.e., the African, Asian and South American continent). The PCAs include charcoal production per capita (Charcoal) for FAO and UN data, deforestation, development indicators (GNI and HDI), and governance richness. WGI governance quality indicators, included Voice and Accountability (GQ_VaA), Political Stability (GQ_PS), Government Efficiency (GQ_Eff), Regulatory Quality (GQ_RQ), Rule of Law (GQ_RoL), and Corruption control (GQ_Cor) (See Table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement.

in forest governance quality (Nandha 2013). The relationship may, however, also suggest the opposite; governance quality may increases a country's human development status and financial resources, potentially allowing countries to control charcoal production levels and efficiently implement policies that reduce deforestation (Afawubo and Noglo 2019, Umemiya *et al* 2010).

Limited effects of charcoal production per capita on deforestation may result from the multifaceted nature of tropical deforestation, caused by multiple drivers, e.g., wood logging for other purposes and agriculture (Houghton 2012, Hosonuma *et al* 2012). Additionally, charcoal production mainly occurs through selective tree cutting, a method resulting in forest degradation rather than deforestation (Woollen *et al* 2016, FAO 2017) – only 27-34% of all woodfuel production causes deforestation (Bailis *et al* 2015).

Overall, our results suggest a limited influence of formal institutions on charcoal production and deforestation, potentially because informal institutions still exert a strong influence (Secco *et al* 2014). This suggests the need to include effects of informal institutions in forest governance impact assessments (Secco *et al* 2014, FAO and UNEP 2020), which requires global data on informal governance systems and their governance quality. The weak effects of formal governance on charcoal production and deforestation contrast with results of a recent review of 28 papers, which shows positive impacts of governance quality on forests (Fischer *et al* 2020). The reasons for the mismatch between our study and the review of Fischer et al. (2020) likely relate to differences in methodology and scope. Fischer et al. (2020) organizes information on governance according to categories proposed by the Word Resources Institute, which is used to assess direct effects of forest governance on deforestation based on local, regional, national and multi-national studies, which mainly originate from Asian and South American countries (only 3 studies regard the African continent). In contrast, we use global governance quality indicators and develop a typology based on USAID reports that provides relatively consistent country-level information, including information on the majority of African countries. It is likely that the weak effects of governance quality on deforestation we find on a global scale relate to the inclusion of countries from the African continent, which exhibit high deforestation. Nonetheless, and more importantly, our findings for Asian and South American countries are consistent with those of Fisher et al. (2020), indicating that high governance quality in these continents corresponds to low deforestation. The contrast in findings between our study and that of Fisher et al. (2020) highlights challenges in global scale assessments of forest governance effects on deforestation, as well as in the comparability of results from global studies of different scopes that utilize different approaches and sampling designs.

### *4.2 Impact of governance systems characteristics on charcoal production and deforestation*

Our observation that certain countries that provide tenure rights to regional governing bodies have a relatively lower charcoal production per capita is in line with theoretical and empirical studies indicating that regional scale governance is most appropriate to tackle natural resources governance, because it strengthens governance networks, provides equal access to decision-making, enables more voices to be heard, and distributes power (Campbell 1996a, Sedlacek and Gaube 2010). It is, furthermore, in line with literature that indicates that decentralized governance is more effective than centralized governance (Campbell, 1996; Morrison, 2014; Ribot, Agrawal, & Larson, 2006), and supports theories of polycentricity, which argue for redundancy in governance systems to increase collaboration between governing bodies (Carlisle & Gruby, 2019; Ostrom, 2001). As the majority of countries that assign tenure rights to regional/sub-regional governing bodies are located in Asia and South America (**Supplementary Materials figure B2 and B3; figure 5**), the relatively lower charcoal production per capita can be explained by mixed effects of relatively higher governance quality related to decentralization and higher development status, which fosters energy transitions and causes charcoal makers to refrain from production. This also indicates a commodification of charcoal.

Our observation that local tenure may potentially be associated with deforestation based on separation between governance systems with and without local tenure in the PCA space contrast with literature that highlights the importance of local tenure rights in the adoption and implementation of sustainable forestry (Arnot *et al* 2011). However, the results are in line with literature that finds variable effects of decentralization on forest outcomes, which affects the success of forest policies, such as REDD+ (Larson and Petkova 2011), as well as with studies that show better outcomes for forest conservation in state-owned forests (Robinson *et al* 2011). An alternative explanation of the results may be a mismatch between the formal distribution of tenure rights and the ability of governing bodies to exercise those rights (i.e., tenure security) (Robinson *et al* 2014a). A recent meta-analysis shows that tenure security associates with lower levels of deforestation in any form of tenure because it reduces the incentive of governing bodies to tend for forest resources (Robinson *et al* 2014a). Therefore, our results might indicate that local governing bodies may have inadequate tenure security to exercise tenure despite formal distribution of tenure rights, which could explain on average slightly enhanced deforestation and charcoal production observed for those governance systems that provide tenure rights to local governing bodies.

Potential negative effects of local tenure on deforestation and the control of charcoal production could also indicate that local formal and informal institutions do not operate independently. Previous studies suggest that informal institutions may substitute formal ones in case of dysfunction (Osei-Tutu *et al* 2015). In these countries both formal and informal institutions may remain non-functional, causing an institutional gap that allows for illegal forestry practices (Osei-Tutu *et al* 2015), which may explain the higher deforestation levels observed. This may result from limited funding transferred by national to regional/sub-regional governing bodies (Andersson *et al* 2006, Agrawal and Ribot 1999), and other forms of elite capture (Persha and Andersson 2014).

Our observation that distribution of tenure, rather than enforcement rights, may potentially influence outcomes of forest governance is in line with studies that highlight the importance of tenure right distribution for effective forest governance (Larson and Dahal 2012, Larson 2011) and local participation (Nie 2018, Schreckenberg and Luttrell 2009). The low effect of enforcement may relate to influences of informal institutions, suggesting that enforcing governing bodies currently may not have the implementation power they should to ensure percolation of formal institutions. Reconciling polycentricity with the need for percolation of formal institutions requires further examination and research (Osei-Tutu *et al* 2015). Our results also highlight the need to further examine whether regional/sub-regional governing bodies could serve to bridge formal and informal institutions to foster bidirectional percolation of institutions bottom-up and top-down.

### *4.3 Data limitations and lessons learned*

We obtained different results between charcoal production estimates provided by the UN and FAO. This variability may result from different definitions, data collection methods and sets of countries that submit the UN Energy Statistics Questionnaire and the annual survey by FAO Forestry Division. Although we found a significant positive relationship between charcoal production data from UN and FAO, we also found substantial differences between countries. Thus, we suggest caution when interpreting global charcoal production data. A range of other factors are known to impact charcoal production, such as export (Proskurina *et al* 2019), demand, and policy instruments and programs, including financial investments to promote alternative energy sources (FAO 2017) and alternative income sources for forest adjacent communities (Cotton *et al* 2021, Zulu and Richardson 2013), which may overshadow impacts of formal forest governance. Additionally, charcoal is mainly produced by rural citizens but mainly consumed by urban citizens (FAO 2017), indicating that the ratio between urban and rural citizens may affect relative measures of charcoal production per capita, either enhancing them (in case of large rural populations who do not depend on charcoal) or lowering them (in case of large urban populations who depend on charcoal). Finally, the governance data used in this study does not directly reflect forest governance quality, and GNI and HDI may not directly correspond to financial investments and knowledge in forestry, while other social-economic factors, such as infrastructure, may also affect development (Fan *et al* 2016) and governance (Houballah *et al* 2020). We recommend that future studies explore effects of indicator choice and their relationships.

We acknowledge that some aspects of governance systems may not have been mentioned or have been left out entirely from the USAID reports we based our forest governance typology on (Anon 2020). We were only able to retrieve information on tenure right distribution across governing bodies from the USAID reports, and we acknowledge that additional factors besides tenure distribution affect governance outcomes, such as access of governance bodies to finances and tenure security (Asaaga *et al* 2020, Robinson *et al* 2014a). Additionally, the typology does not regard country-specific nuances. For instance, in Tanzania, no specific individual enforcement and tenure rights exist for charcoal production (United Republic of Tanzania 1982), and although regional governing bodies are involved in forest governance, they derive limited funding (Milledge *et al* 2007). Hence, decentralization may not automatically result in equitable distribution of rights and financial resources to involved governing bodies, potentially explaining disparities in governance quality of decentralized countries. Additionally, governing body richness does not provide complete insight in the polycentricity of governance systems, as governing bodies may have been assigned completely different tasks, potentially resulting in fragmentation rather than redundancy. A complete assessment of fragmentation and polycentricity requires full knowledge on overlap and complementarity of governance tasks among all governing bodies involved, calling for a more detailed assessment of countries' forest acts and a more advanced typology of forest governance systems. Thus, country/continent-specific (informal) governance aspects may have inhibited us to find clear patterns in governance and further research is necessary to understand their effects on charcoal production, deforestation and governance quality. Finally, we did not specifically regard the wellbeing of people involved in the charcoal value chain (Ece 2017), which may be influenced by governance systems and should be considered when designing them (van 't Veen *et al* 2021). Our data exploration can, however, be used to inform future local studies and policy projects on global effects of forest governance by providing indications about important governance and development factors, which influence charcoal production and deforestation.

## 5. Conclusion

Charcoal production causes up to 7% of annual deforestation and forest degradation, while providing energy for hundreds of millions of livelihoods. High levels of charcoal production and consequent loss and degradation of forests may be mitigated through high quality and effective governance, which requires large financial investments. We explore relations between forest governance, development, charcoal production and deforestation. Our results to date suggest that countries' development status affects charcoal production rather than their governance quality. We also find indications that regional/sub-regional governing bodies may potentially serve as levers to foster transitions to decentralized, polycentric or regionalized governance, which could lower charcoal production levels. These results may be explained by mixed effects of high governance quality related to decentralization and development, fostering energy transitions and commodification of charcoal in Asian and South American countries. Our findings should be regarded with caution because of strong effects of informal governance on charcoal production. However, our study highlights countries that lead the way to higher governance quality and lower charcoal production and deforestation, and we see a potential opportunity for regional/sub-regional governing bodies to act bridge between formal and informal institutions.

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## Author contributions

The author contributions are based on CRediT (Contributor Roles Taxonomy), which aims to recognize individual author contributions, to facilitate collaborations and to diminish disputes among authors (https://www.elsevier.com/authors/policies-and-guidelines/credit-author-statement).

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# Chapter 9

## Synthesis

## 9.1 Synthesis

Presently, 75% of the Earth's surface is measurably influenced by human footprint, and pressures on ecosystems and biodiversity are increasing (Venter *et al* 2016). Yet, despite the wide span of social-ecological systems globally, humanity still faces challenges in sustaining the balance between growth and exploitation of natural resources (Lampert 2019). One social-ecological system in which this struggle is faced is the charcoal production system, which provides an important energy and income source to hundreds of millions of people and simultaneously causes forest degradation and 7% of deforestation worldwide, including as a by-product of agriculture (FAO 2017). During my PhD I have studied different social and ecological components of charcoal production systems, their interactions and their response to interventions that aim to initiate sustainability transitions, in particular governance transitions. This has not only allowed me to fill important knowledge gaps on charcoal production systems specifically but also enabled me to shed light on knowledge gaps in social-ecological system science in general. In this synthesis, I discuss the varying components of charcoal production systems and their interactions, using the social-ecological systems framework and the design principles for sustainable management of commons of Elinor Ostrom as guidelines to organize findings.

### 9.1.1 Spatiotemporal effects of transitions in charcoal production systems on forest use

In **Chapter 3**, my co-authors and I theoretically examined long-term effects of transitions in charcoal production systems on the interaction between woody biomass and charcoal biomass, allowing us to shed light on the ways charcoal producers may harvest forest resources. We find that transitions to alternative charcoal production systems, such as communal management or private systems, are unnecessary at low to medium demand. However, at high demand, transitions from unregulated production to regulated production may foster sustainability on the long term and prevent forest resource collapse, in particular when combined with interventions that increase carbonization efficiency and/or reduce demand. Thus, our modelling exercise indicates that transitions in governance systems can theoretically balance natural resource use and exploitation in charcoal production systems that are prone to overexploitation, provided that a mix of strategies are implemented that consider levels of forest biomass present, forest carrying capacity and the experienced demand (Fig. 9.1). In conclusion, our study highlights multiple pathways to sustainability, in line with opinion papers that recommend the implementation of multiple interventions to combat charcoal-related deforestation (Njenga *et al* 2013).

The study of **Chapter 3** is in line with social-ecological systems theory that suggests that humans have the power to shape the relationship between nature and society through governance (Ostrom 2009). The observed social-ecological advantages of governance transitions are in line with studies that highlight positive effects of community-based natural resources management (CBNRM) (Deschamps 2000, Fajar and Kim 2019, Nath *et al* 2016) on the extent of the area covered by natural resources. However, more quantitative evidence is necessary on the impacts of CBNRM on natural resource use and conservation (Pero and Smith 2008), potentially through self-monitoring by communities (Brown et al. 2010). Besides this, results are in line with studies that find positive effects of privatization (Nguyen *et al* 2010), possibly because privatizing land provides those who tend for it with a greater incentive to sustainably manage the natural resources growing on their land (Nguyen *et al* 2010). However, transitions to private systems are also criticized as often more attention is paid to its social-economic performance than its ecological consequences (Prizzia 2002). For instance, the replacement of natural forests with plantations has been shown to negatively affect biodiversity (Brockerhoff *et al* 2008). Nevertheless, practitioners argue that the concept of privatization should not be abandoned; rather efforts should be made to better tailor privatization practices to local conditions (Kikeri and Nellis 2004).

The study of **Chapter 3** provided hypotheses on the potential impacts of transitions in charcoal production systems on forest resources. In **Chapter 4** and **Chapter 5**, my co-authors and I empirically assessed charcoal production activities in miombo woodlands of Tanzania, in three villages under open access and three under the CBNRM project, Transforming Tanzania's Charcoal Sector (TTCS), of Tanzania Forest Conservation Group (TFCG). In **Chapter 4**, we conclude that a combined remote sensing method that includes satellite imagery of different spatial and spectral resolutions can

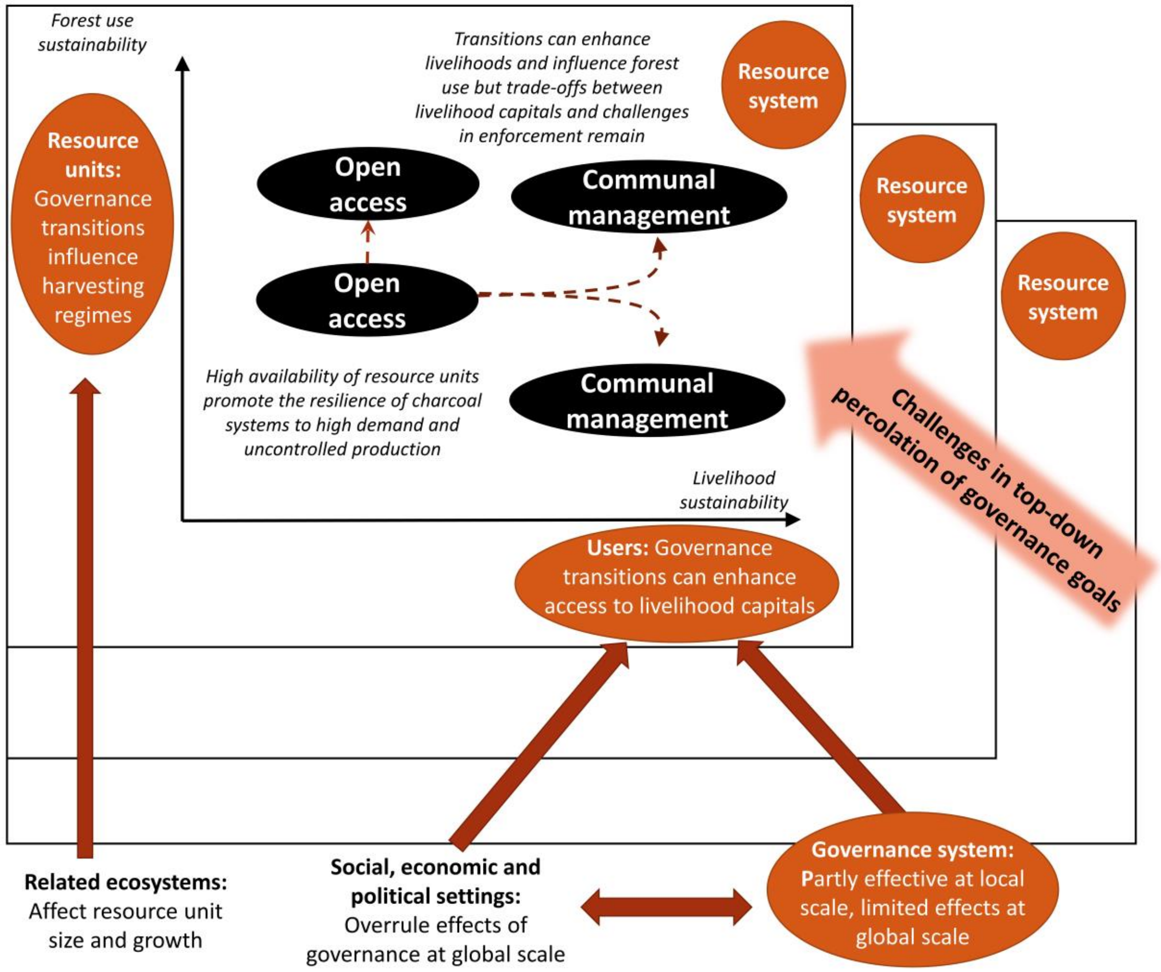

**Figure 9.1** The conceptual framework of this thesis (see Fig. 1.4) including the main conclusions derived from the Chapters, which provide answers to the four main research questions. The dotted arrows in the graph depict expectations of potential trajectories initially observed in the study villages. Resource units are forest biomass resources, users are charcoal producers, resource systems are natural resources within a defined boundary (e.g., a forest in a village, district or nation), and governance systems are sets of formal laws and formal and informal rules and regulations about forest use and conservation that apply in a resource system. Related ecosystems are those forest ecosystems in which charcoal production takes place and social, economic and political settings are the social, economic and political settings that influence a resource system. The graph in the middle indicates the interaction between the resource unit and user components of charcoal production systems and in its effect on transitions in charcoal production systems, which is the interaction that can readily be assessed when we theoretically or empirically combine data of resource units and users. In total, we tested three scenarios: (i) A reduction in demand and/or a transition to alternative energy sources, (ii) laws, rules and regulations aimed at controlling production and at enhancing charcoal producer livelihood sustainability at high demand, and (iii) uncontrolled production at high demands. We hypothesize that these scenarios result in three alternate states in charcoal production systems: (i) $S_r$: Sustainable use of forest resources at the expense of charcoal producer livelihood sustainability, (ii) S: Sustainable use of resources and sustainable livelihoods of charcoal producers, and (iii) U: Both unsustainable use of resources and livelihoods of charcoal producers.

distinguish charcoal sites with high robustness (i.e., a high chance that charcoal has been produced in the areas detected as charcoal site). This, because it takes advantage of spectral signals of different features of charcoal sites, namely the kiln/kiln scar, the surrounding bare soil and the harvesting area for charcoal production.

The results of **Chapter 4** are in line with prior studies that show that charcoal sites can be distinguished using satellite data, including VHR imagery (Bolognesi *et al* 2015, Sedano *et al* 2016), lower spatial resolution Sentinel-2 imagery with relatively high spectral resolution (Nakalema 2019), and even lower spatial and spectral resolution Landsat-8 imagery (Sedano *et al* 2020a, 2020b, 2021). Additionally, it is in line with prior studies that show that combining remote sensing outputs of VHR and Landsat-8 imagery may improve charcoal site detection (Sedano *et al* 2021). Nevertheless, our study greatly adds to existing literature, as it zooms into challenges related to cutting practices, canopy cover and data availability, as well as the ways to overcome these challenges using different types of satellite imagery combined in a single approach. Besides this, we, for the first time, zoom into the spectral signals of charcoal sites observed on different satellite imagery in order to explain the reasons behind their detection at different spatial and spectral resolutions. This answers questions about the spectral signals that are characteristic to charcoal sites and the ways in which they vary between satellite imagery types. By adjusting results for spatial uncertainty, we, for the first time, provide ranges in the robustness of charcoal site detection, highlighting areas that are most difficult to detect (i.e., selectively cut areas) and areas that are easiest to detect (i.e., large clear cutting areas). Our results are one of a kind because of the unique combination of two classification outputs and one visual imagery inspection method, and because to our knowledge no study has yet monitored charcoal production sites through remote sensing in highly populated areas within defined village boundaries under distinct harvesting regimes.

Overall, **Chapter 4** identifies opportunities and challenges in the monitoring of common pool resources, specifically forests harvested for charcoal production. The method developed in **Chapter 4** highlights opportunities to actively use remote sensing in charcoal site monitoring under different forest management regimes. This may ultimately allow policy makers and practitioners to meet an important design principle to manage the commons, namely monitoring of users in social-ecological systems to assure accountability (Mcginnis and Ostrom 1992). Currently, the application of remote sensing in natural resource monitoring is on the rise (Navalgund *et al* 2007). For instance, in Brazil forests are continuously monitored through remote sensing (Fuller 2006), and remote sensing is used for environmental impact assessments in India (Navalgund *et al* 2007). Besides this, forests are globally monitored by Global Forest Watch, which provides anyone interested with the latest tools, technology and data to monitor and protect forests (https://globalforestwatch.org/, last accessed the 9th of March 2022). Practitioners praise the synoptic overview and repetitive coverage of satellites to provide more regular information over continuous areas to monitor changes in natural resources (Navalgund *et al* 2007). Therefore, it is not implausible to actively detect charcoal sites through remote sensing for monitoring and enforcement in the future, in particular since other studies have proposed this before (Sedano *et al* 2016).

Nevertheless, **Chapter 4** also highlights challenges in the use of remote sensing to monitor charcoal sites. First, the developed method does not provide an exact indication of the extent of the area subjected to charcoal production, which may challenge monitoring practices. Instead, the identification of charcoal sites detected with high robustness allows for an impact assessment of charcoal production on forest biomass and biodiversity. For instance, scientist and practitioners could identify the most robustly detected charcoal sites and conduct empirical research on tree biodiversity in them, reducing the amount of time and effort it takes to find these sites on the ground. This would also allow them to improve their sampling strategy by selecting sites that are randomly distributed through the landscape or subjected to similar or distinct geographical conditions (e.g., located at similar or different elevation levels). Second, the remote sensing method relies on field data to validate its outputs. Gathering this field data is time consuming and expensive, in particular when expanding the remote sensing of charcoal sites to other tropical regions subjected to different forest ecosystems. A potential solution to this problem could be citizen science or community monitoring, where charcoal producers or other villagers gather field data on charcoal sites and send it to analysts for processing. In the future, policy makers may process citizen science data from multiple communities and compare them to identify opportunities to improve charcoal-related policies. Finally, our method is yet unable to distinguish between charcoal production for the purpose of charcoal production and charcoal production for the purpose of agricultural expansion. In areas where charcoal is produced for the sole purpose of charcoal production, forest regeneration can take place (Chidumayo 2004). Hence, these areas are likely to experience forest degradation, rather than deforestation, in particular if charcoal is produced through selective cutting, which leaves tree coverage (Kalaba *et al* 2013). In contrast, areas subjected to charcoal production as a by-product of agricultural expansion are subjected to clear cutting and forest regrowth will likely not take place, causing deforestation (Iiyama *et al* 2017). Momentarily, agriculture is the greatest cause of deforestation in many regions in the tropics (Houghton 2012), and the income derived from charcoal production often provides starting capital for farmers (Zulu and Richardson 2013). Therefore, future research may assess whether a differentiation can be made between the two types of charcoal sites, e.g., by combining remote sensing methods that distinguish agricultural land with those identifying charcoal sites.

The remote sensing method developed in **Chapter 4** allowed my co-authors and I to assess charcoal site patterns, including their size, shape, density and distribution, in response to three social-ecological drivers (biomass prior to production, travel distance and governance), as described in **Chapter 5** of this thesis. It is important to understand effects of social-ecological drivers on charcoal site patterns because the way forests are harvested can influence forest growth and biodiversity (Ding *et al* 2012, Gatti *et al* 2015). Overall, we find limited direct effects of forest biomass prior to charcoal production on charcoal site patterns but we do find characteristic peaks in charcoal sites numbers, their size and aboveground biomass available in them under open access. We find that governance (i.e., the laws, rules and regulation for the use of forest resources) influences charcoal site patterns throughout the landscape because we find significant differences between villages under open access and villages under CBNRM. Nevertheless, charcoal producers do not completely adhere to laws, rules and regulations concerning charcoal production as defined in the CBNRM harvesting plan. Although they produce in smaller harvesting areas as dictated, production does not only occur inside the designated area for charcoal production but also in other village areas. We argue that this potentially relates to inequality in access to forest resources between the two study village types, as villages under CBNRM are smaller than the open access villages and have less available forest biomass, making it more challenging for charcoal producers to reconcile sustainable production with daily needs provisioning (Fig. 9.1). This argument is in line with our conclusion in **Chapter 3** that communal management is best implemented at medium to high forest biomass availability, as this allows for a continuation of sufficient charcoal production to support charcoal producer livelihoods (van 't Veen *et al* 2021). The mismatch between governance goals and reality may, however, also result from differentiations between perceptions on sustainable management of the forest. For instance, previous studies on community-based management of wildlife indicated that many community members did not support the presence of wildlife in their village forests, which contradicted the sustainability objectives of the implemented CBNRM scheme (Mbaiwa 2004).

Our finding that access to forest resources, their growth rates and carrying capacity may affect forest use for charcoal production sheds light on one of the secondary social-ecological system variables, namely the productivity of the system (Ostrom 2009). This variable indicates that management of commons is more successful when abundant natural resources are present (Acosta *et al* 2018, Van Laerhoven and Ostrom 2007), otherwise, it proves difficult for users to recognize the need to manage forests sustainably for future production (Nagendra and Ostrom 2014). Although this effect is not always strongly observed in literature (Perrotti *et al* 2020), we find hints that charcoal producers experience shortages in aboveground biomass in the livelihoods surveys conducted for **Chapter 6** and **Chapter 7** of this study. For instance, several charcoal producers operating in villages under CBNRM mentioned that there are not enough trees present in the village forest to continue charcoal production over the coming years. This comment suggests that the related ecosystems aspect of social-ecological systems (Fig. 9.1) needs further attention, e.g., through the inclusion of an ecological rules component, as suggested by Epstein et al. (2013). This is in particular important for charcoal production systems because of the high variation in harvesting regimes (Maleki *et al* 2021, Kalaba *et al* 2013), which causes different regeneration rates and biodiversity (Kalaba *et al* 2013). It is also important because charcoal production takes place in a wide variation of forest ecosystems across the tropics, ranging from tropical dry forests to rainforests (Wright 2005), each with their own (functional) diversity, community composition and productivity (Gibson et al. 2011).

#### *9.1.1.1 Effects of governance transitions on forest use in context of Ostrom's design principles*

The mismatch we observed between governance goals and reality in our study villages under CBNRM may indicate that some of the eight design principles for sustainable management of commons are not met in our study system. These could potentially be clear boundaries, graduated sanctions for offenders, monitoring, and/or the fit of rules and regulations to local circumstances (Mcginnis and Ostrom 1992). Although our study villages theoretically have clearly defined boundaries, the fieldwork assistants, who conducted livelihood surveys for **Chapter 6** of this thesis, indicated that government officials and charcoal producers alike communicated challenges in protecting them. For instance, members of the village government of one of the villages under CBNRM stated that the stone with which they mark their village boundary had been moved around and that it, at a certain instance, disappeared entirely. Additionally, ample charcoal producers stated that they thought that producers from outside their village area produced charcoal in the forests within their village boundary and that they were responsible for illegal production. This might potentially indicate that Ostrom's design principle of clearly defined boundaries of commons are not met sufficiently in our study villages, which could negatively impact governance quality, as the system becomes more prone to cheating (Yasmi *et al* 2007). However, the opposite could also be true, as replacement of soft traditional boundaries with hardened static boundaries can induce conflict and erode social networks, which are important for good governance (i.e., effective, efficient and fair governance in line with rule of law and free of corruption) (Bennett, Ainslie, and Davis 2010; Brewer 2012). Hence, it could be that the strict boundaries of the designated harvesting area for charcoal production conflict with legacy practices and induce challenges in defining and enforcing tenure rights, which may explain production outside of these areas. In contrast, selective production in small harvesting areas may fit previously present local practices, explaining the smaller and more regular sites observed in villages under CBNRM. This discussion is in line with studies that found that the social-ecological success of CBNRM is often more influenced by the characteristics of the system it replaces than by the content of the implemented governance (Dressler *et al* 2010). However, it could also be that the smaller more regular charcoal sites are the product of effectively enforced laws that ban charcoal as a by-product of agricultural land clearance. This further emphasizes the need for a remote sensing method that distinguishes between charcoal production as by-product of agricultural expansion and charcoal production as final product.

Although producers mentioned the existence of sanctions for those who do not comply to the governance regime, several mechanisms were mentioned by charcoal producers through which cheaters were punished, namely differences in the heaviness of fines, warning systems, disposal of illegally produced charcoal, and the placement of bans on production. On the one hand, this may indicate that producers lack knowledge on the sanctioning system in place and/or that there is room for negotiation when offenders are caught. On the other hand, comments of charcoal producers that an offence results in an immediately ban from production may indicate that sanctions are, at least in some cases, or to the knowledge of several interviewed charcoal producers, not graduated, meaning that no system is in place that gradually enhances punishments for offenders to assure compliance in the future. This may potentially cause resentment with offenders who have been banned from production, potentially resulting in illegal production by these offenders (Mcginnis and Ostrom 1992). As charcoal production occurs outside of the designated harvesting area, villages under CBNRM may face challenges in monitoring production practices. Although, these challenges have not been addressed in our survey, many producers operating under CBNRM indicated that there might be offenders operating in their village. Besides this, we found that some interviewed producers burned charcoal on their agricultural land instead of in the designated charcoal production area, explaining why we find production activities in agricultural areas with our combined remote sensing approach of **Chapter 4**.

Finally, our findings may indicate that the rules implemented through the CBNRM harvesting plan may not completely fit local circumstances. In principle, CBNRM fits in the national framework for local governance of forest resources as defined by the government of Tanzania (USAID 2017). However, decentralization in Tanzania started in the mid-1990s (Cleaver and Toner 2006), which provided communities a relatively short time to get used to communal management of forest resources, even though communal decision-making is widespread (Persha and Blomley 2009). Additionally, a recent study about the TTCS project argues that there may be connections between the TTCS project and issues faced by villagers, including a loss of farmland, and continued struggles over compensation, resulting in resistance (Mabele 2019). Although we have not encountered strong evidence for resistance by charcoal producers towards the TTCS project, as charcoal producers generally appeared to be (highly) positive about it, several producers were dissatisfied with the project, stating that they feel that it does not provide them the promised benefits or that it does not protect their village forest. Mabele (2019) suggests that multi-dimensional policy frameworks could be used to expose aspects of forest conservation that are locally valued and aspects that are contested, to allow for an adaptation of implemented forest management policies to local contexts. This may provide an opportunity to closer adjust the implemented CBNRM scheme introduced by TFCG to local circumstances over the years to come, based on a better understanding of the social-ecological challenges the scheme faces.

#### *9.1.1.2 Conclusion on the effects of governance transitions on forest use*

In conclusion, in **Chapter 3**, **Chapter 4** and **Chapter 5**, my co-authors and I find that transitions in charcoal production systems have the power to alter forest use, in particular transitions in governance. Yet, empirically observed mismatches between harvesting guidelines dictated by the CBNRM harvesting plan and reality indicate challenges in the effective implementation of communal management in charcoal production systems. This mismatch highlights difficulties in the percolation of governance goals at a local scale, something that is also observed on a global scale in **Chapter 8** of this thesis (Fig. 9.1). Unfortunately, we were unable to provide insights on future environmental sustainability in the charcoal production systems of our case study. Based on current production patterns and biomass changes observed in the villages and initial assessments using the stylized model developed in **Chapter 3**, we expect a potential reduction in forest biomass in one village under CBNRM and a slight increase in forest biomass in the other two villages, while we expect a larger increase in the two open access villages, given the high access to forest biomass within village boundaries and the relatively large village sizes. Future studies may empirically compare the sustainability of forest harvesting practices in villages under open access and communal management in terms of their ability to limit forest degradation, deforestation and biodiversity loss. A potential approach could be a space-for-time assessment of biomass growth and tree biodiversity in charcoal sites created over the past decade (e.g., from 2014 to 2022), using the remote sensing method developed in **Chapter 4**. Such predictions may be used to conduct fieldwork on biomass and tree biodiversity in sites subjected to charcoal production in different years. This data could be extrapolated over the entire study area and integrated in the model of **Chapter 3**. Besides this, the model of **Chapter 3** and the findings of **Chapter 5** could inform and parameterize a spatially explicit model to move towards improved predictability of charcoal patterns in the landscape to inform future changes in charcoal production systems.

### 9.1.2 Effects of transitions in charcoal production systems on producer livelihoods

In **Chapter 6**, my co-authors and I studied the social networks of charcoal producers. We show that CBNRM can positively influence the density of connections between charcoal producers and, to limited extent, between producers and members of their village government. This most likely results from a formalization of collaboration through charcoal producer associations, shared management and decision-making, and training schemes. Dense and decentralized social networks are important for trust, capacity building and reciprocity (Bhandari and Yasunobu 2009, Nenadovic and Epstein 2016, Nooteboom 2007), which can positively influence governance (Grafton 2005, Hawkins and Maurer 2010, Musavengane and Kloppers 2020). Positive effects of communal management on social networks of users have been observed in prior studies (Becker 2001), and formalization of interactions have been shown to play an important role in network building (Maas *et al* 2014, Serra and Davidson 2021). However, impacts of social networks on governance depend on the types and strengths of social networks and the behavior it should foster (Nepal *et al* 2007). To our knowledge social networks of charcoal producers have not been studied before; hence **Chapter 6** greatly adds to knowledge on charcoal producer livelihoods. Additionally, we found limited direct comparisons between systems under communal management and those under open access. Therefore, we conclude that our study, for the first time, provides important insights into the effects of governance transitions in charcoal production systems on access to an important livelihood asset: social networks.

In **Chapter 7**, my co-authors and I further examined different assets (i.e., livelihood capitals) charcoal producers need to sustain their livelihoods to put the social network results obtained in **Chapter 6** in perspective. We assessed synergies and trade-offs between natural capital (i.e., forest resources), financial capital (i.e., income and charcoal produced), human capital (i.e., knowledge and health), social capital (i.e., social interactions and support), and physical capital (i.e., physical assets of charcoal producers, such as housing). By developing a number of indicators for each capital, using answers to the same livelihood surveys conducted for **Chapter 6**, we were able to analyze differences in the access charcoal producers have to them, as well as correlations between them. This provided a first time overview of livelihood synergies and trade-offs of charcoal producers under distinct governance regimes through counterfactual analyses to further understand effects governance transitions may have on charcoal producer livelihoods and forests. Our results highlight that governance transitions have the power to foster access to (specific aspects of) livelihood capitals. This may increase the livelihood sustainability of charcoal producers, defined as access to all livelihood capitals necessary to sustain one's livelihood (Scoones 1998). Nevertheless, we encounter strong trade-offs between the income charcoal producers receive per bag and other livelihood capital indicators, which indicates that enhancing access to one livelihood capital may come at the expense of other livelihood capitals. This is due to the transformation of financial capital into other livelihood capitals through a CBNRM revenue-sharing scheme, which benefits individual charcoal producers and the communities they are part of in terms of forest monitoring and conservation efforts and community development. We find that livelihood capitals are not singular because we observed trade-offs between indicators of the same capital, such as trade-offs between cooperation with others and perceived support from others (both social capital). Finally, we find that the impact of governance is likely complemented by local social-ecological dynamics because access to livelihood capitals, their trade-offs and synergies differ between villages with the same governance system in place. We conclude that fostering livelihood sustainability through governance transitions is complex in social-ecological systems but we identify important lessons to improve governance to assure that it benefits both people and forests.

Both **Chapter 6** and **Chapter 7** reveal the power of governance to enhance access of charcoal producers to livelihood capitals. Since many CBNRM experience large mismatches between governance goals and reality and even complete failure (Lyons 2013, Mohammed and Inoue 2012b), our positive outcome highlights the quality of the TTCS project implemented by TFCG. The ability of the TTCS project to enhance access to charcoal producer livelihood resources may relate to the construction and implementation of the project. Previous studies on CBNRM highlight key principles for effective CBNRM, which includes public participation and participatory decision making, social networks and collaboration among partners, equitable distribution of received benefits, effective communication, continuous information acquisition, a devolution of power to local communities, gaining public trust, monitoring schemes to assure accountability, adaptive leadership and schemes for conflict resolution (Gruber 2010). The TTCS project, in theory, adheres to the vast majority of these principles because it promotes participatory management of the forest to enhance collaboration and monitoring, as it provides training schemes to transfer knowledge, and because it fosters access to formal institutions, such as charcoal producer associations, that promote communication and participatory decision making (Ishengoma *et al* 2016). Besides this, TFCG assured the devolution of power to local communities by guiding them through the application process to obtain legal rights over the extraction of woody biomass in a designated areas on their village land (Ishengoma *et al* 2016). Overall, our findings indicate the potential suitability of the TTCS project for upscaling CBNRM of charcoal production over large regions in Tanzania, as well as the importance of continued monitoring of project outcomes to pinpoint the reasons behind the positive influence the TTCS project has on livelihood capital accessibility and the challenges the project faces.

The dense and decentralized social networks observed in villages under CBNRM are expected to positively influence forest governance (Grafton 2005, Hawkins and Maurer 2010, Musavengane and Kloppers 2020). Hence, the formation of dense and decentralized social networks may have contributed to promoting charcoal producer adherence to rules about the size and shape of charcoal sites as specified in the CBNRM harvesting plan (see **Chapter 5**). This positive effect could have been fostered through knowledge sharing, as producers in villages under CBNRM more often indicated that they share knowledge with each other than producers in villages under open access. Yet, **Chapter 7** reveals that charcoal producers in open access and CBNRM villages have similar levels of human capital, and we observe limited positive correlations between social capital and human capital indicators. This may be a result of generally great knowledge about charcoal production technologies and forests in local communities, which is supported by literature that finds high levels of knowledge about natural resources locally (Milupi *et al* 2017, Ofori *et al* 2014). It could also be that the questions asked in our livelihood surveys were too general to capture the differences in knowledge between charcoal producers operating under open access and those operating under CBNRM. For example, we did not ask questions about the knowledge of charcoal producers on the governance regime in place or forest management practices. Besides this, training schemes may not have effectively enhanced knowledge of charcoal producers on the impact of their practice on forests in their village or forest management. For instance, charcoal producers may be more intensively trained on the manner in which to produce charcoal (e.g., production in a squared 50 m harvesting area (Ishengoma *et al* 2016)), whereas they might have been less intensively trained on the boundaries of the designated area for charcoal production and the plots in which they may produce charcoal in specific years. This may potential explain production of charcoal outside of designated areas found in **Chapter 5**, which may potentially relate to the strategy of TFCG to provide training about good governance to staff of Kilosa District, Village Council members and the Village Natural Resources Committee but not to charcoal producers themselves (Ishengoma *et al* 2016). Potentially it was challenging for District and Village Council members to communicate the principles of good governance to charcoal producers following their training. Future studies could monitor the knowledge exchange happening between charcoal producers and their general awareness of forest boundaries, the designated area of charcoal production and years in which the 50 m plots within the designated area should be harvested.

Besides potential limitations of knowledge about designated area and good governance, mismatches between governance goals and reality may also relate to trade-offs observed between income per bag and other livelihood capitals under CBNRM observed in **Chapter 7**. In our qualitative data, we find hints that charcoal producers struggle to obtain enough income from charcoal production under CBNRM, in particular since many producers indicated that the income they received per bag dramatically dropped up to 50% over the past five years. This is likely a result from higher prices per charcoal bag for intermediates (i.e., buyers of charcoal bags) under CBNRM than under open access, as taxes are to a large extent evaded under open access systems and risks of fines are low (Lund 2007, Mustalahti and Lund 2010). The consequence of this competition between CBNRM and open access system is that not enough intermediates are attracted by Village Councils to buy charcoal bags. At the same time challenges in the negotiation of prices due to a lack of bargaining power may occur. Our qualitative results reveal that the drop in price per bag motivated some charcoal producers in CBNRM villages to halt their charcoal production activities because it did not provide them enough income to sustain their livelihoods, despite the increased access to other livelihood capitals at individual and community level through the CBNRM revenue-sharing scheme. In response to price drops, these charcoal produces may have shifted to areas outside of the designated area for charcoal production to avoid overharvesting this part of the forest or to avoid patrols that monitor charcoal production within this area. Tax avoidance as a consequence of a discrepancy between direct financial benefits under legal versus illegal forest use has been observed in previous studies on CBNRM of forests (Ameha *et al* 2014, Mohammed and Inoue 2012a, Richards *et al* 2003). Although no charcoal producers indicated specifically that they started producing charcoal outside of designated areas, this may be a result of the illegal nature of this activity. We also find indications in the surveys that some charcoal producers produce charcoal from the trees that grow on land they own or lease, even though this is considered illegal in villages under CBNRM. This may explain the wide distribution of charcoal sites throughout the entire extent of CBNRM villages, including areas predominantly dominated by agriculture.

Dissatisfaction with the financial benefits obtained from natural resources exploitation by those extracting it is common under CBNRM schemes (Garner 2012, Measham and Lumbasi 2013), in particular if these do not meet expectations (Mosimane and Silva 2015). Such situations can also reduce trust of people in those who manage shared funds (Mbaiwa 2004), such as the Village Council in case of our study villages under CBNRM. Dissatisfaction may result from a disproportionate focus of CBNRM schemes on nature protection compared to financial benefits for poor local communities, which can in some cases impoverish them more (Dressler *et al* 2010). We find indications for this in our qualitative data because charcoal producers across all three CBNRM villages indicated that their Village Council is not transparent about the community funds they receive and the way they spend them. As mismanagement of funds or elite capture is a common process under CBNRM (Blaikie 2006, Dressler *et al* 2010), an investigation is warranted into the management of communal funding received from the TTCS project by those in charge. Overall, mismatches between expected and actual financial benefits received may threaten the continuation of community participation in and impede upscaling of CBNRM schemes (Silva and Mosimane 2013), which could jeopardize the livelihood benefits the scheme provides in terms of forest management and community development. As financial benefits have been highlighted in previous as the main reason for positive attitudes of local communities towards CBNRM (Blaikie 2006, Dressler *et al* 2010), it is vital to assure that expectations about income from charcoal producers are carefully communicated and met in order to avoid disappointment and potential consequent deviations of harvesting guidelines, such as those observed in **Chapter 5**. This may be achieved by reducing competition between CBNRM and open access systems, by either expanding CBNRM for charcoal production (e.g., based on the TTCS project) over large continuous areas or by reducing incentives for intermediates to buy illegally produced charcoal bags through enhanced control of illegal charcoal transport. Such initiatives may ensure that CBNRM of charcoal production can continue to provide individual- and community-level livelihood benefits.

#### *9.1.2.1 Effects of governance transitions on livelihoods in context of Ostrom's design principles*

The studies of **Chapter 6** and **Chapter 7** provide insights in several of the design principles of Elinor Ostrom, such as allowing producers to engage in decision-making regarding the use of forests to produce charcoal, participatory decision-making about rules and regulations on charcoal production, fitting of rules to local circumstances, and nesting of local commons within a wider network of governing bodies. According to the formal rules introduced under CBNRM and the survey results, charcoal producers are invited to engage in decision-making through formally established associations, indicating that the condition for participatory decision-making and the inclusion of users in this process is met. However, although local government officials and charcoal producers are technically invited to provide inputs on the laws, rules and regulations implemented in villages under CBNRM (Ishengoma *et al* 2016), their input is restricted by overarching nationally defined laws, rules and regulations for the use and conservation of forests in Tanzania (Doggart 2016, Doggart and Meshack 2017). This means that TFCG was unable to adhere completely to the design principles of participatory decision making due to the governance system already in place, potentially resulting in the implementation of laws, rules and regulations that were not completely congruent to local circumstances (e.g., strict boundaries of forest land in the villages). This may signal trade-offs between the principle of participatory decision making by local communities about the governance and management of their forest resources and the principle of nested commons in larger networks of regional and national governing bodies. These trade-offs are highlighted in a previous study on the project, which finds that enhanced regard of local contexts in forest management under CBNRM of charcoal production is necessary (Mabele 2019).

Although participatory decision-making is strongly promoted under the TTCS project through the introduction of formal institutions, such as charcoal producer associations, the commonalities between the harvesting plans implemented across all CBNRM villages (Ishengoma *et al* 2016) suggest that communities may have limited power to influence the primary principles of the implemented forest harvesting plan. The observed similarities are likely related to the relatively strict laws, rules and regulation regarding devolution of power to local communities to manage forest resources implemented by the government of Tanzania (Blomley 2006). In order to extract forest resources legally, local communities need to apply for a Village Land Forest Reserve (VLFR) by submitting a sustainable harvesting plan to their District Council (Doggart 2016). This requires local communities to provide an indication of the location of the VLFR (URT 2002), which may be difficult to obtain. In addition, application for a VLFR requires detailed knowledge about Tanzania's forest law, principles of sustainable forest management and good governance; knowledge local communities often have limited access to (Goldman 2003). All this may potentially challenge adjustments of the forest management plan proposed by TFCG to local contexts by local actors, despite the fact that local communities have sole ownership and decision-making rights over their forest land under CBNRM (Wily 2002). Such potential disconnect between local practices and an implemented management scheme may potentially cause mismatches between local practices and the forest harvesting plan implemented, which could potentially result in disobedience towards some of its practices as observed in **Chapter 5**.

Potential challenges in devolving power to local communities to adjust a forest management plan raise an interesting question about the extent to which communities should be able to influence their forest management practices under CBNRM when they are implemented under the guidance of external actors with expertise in good practices for forest management. On the one hand, it may be desirable to allow communities (e.g., village leaders and charcoal producers) to adjust forest harvesting plans to local contexts from the start of an NGO project to better meet design principles of Ostrom (Mcginnis and Ostrom 1992). Ideally an enabling governance system should be implemented under which communities self-organize to manage their forests because such systems often for decades (e.g., selforganized community forest management in India) (Nayak and Berkes 2008) and may promote more favorable outcomes for natural resource extent and livelihoods than policy initiatives of governance bodies (e.g., observed for farmer managed irrigation systems) (Cox 2014, Lam and Ostrom 2010, Latif *et al* 2014). Potential mismatches between local practices and the implemented forest harvesting plan raises the question whether current forest laws, rules and regulations of Tanzania create an enabling environment for local communities to self-organize. On the other hand, it may be interesting to implement similar forest management based on best practices for forest harvesting and protection at a landscape scale because this promotes comparison and monitoring, and eases impact assessments, e.g., using the remote sensing method developed in **Chapter 4**. Streamlined processes may on the long term enhance adaptive capacity because continuous research and monitoring would allow policy makers to respond to local social-ecological dynamics and mismanagement (Mutimukuru *et al* 2006). Yet, streamlining practices may also result in unnecessary bureaucracy and may overly organize them, which makes it difficult to continue these practices on the long term without interference of a third party (Dressler *et al* 2010).

Although charcoal producers are formally involved in decision-making through charcoal producer associations in villages under CBNRM, many interviewed charcoal producers indicated that they feel that their associations are being abolished or that they do not meet up anymore. Several of these producers plead for the continuation or reestablishment of their association. As reason for the discontinuation of their associations, they often state that the Village or District Council has not prolonged permits to continue them. This suggests challenges in the continuation of formal institutions that foster dense charcoal producer networks, which may threaten the principle of shared decision-making and user participation in this decision-making under CBNRM on the long-term. CBNRM projects or aspects of these project are often discontinued following withdrawal of external parties (Dressler *et al* 2010, Meshack *et al* 2007, Turner 2004) and because of challenges in the devolution of power to local communities, e.g., upon recentralization (Rihoy and Maguranyanga 2007). Statements of charcoal producers that Village or District Councils have not prolonged permits for charcoal producer associations, may indicate that the forest commons in villages under CBNRM are not effectively nested in a wider policy network. This is further indicated by qualitative statements of Village Council members, which indicate that District officers responsible for the management of the VLFR in Kilosa District have not visited their village in over a year. Interestingly, TFCG has put great effort into the establishment of a nested devolved governance regime within Kilosa District, where the District Forest Conservator supervises harvesting for charcoal and timber production together with the Village Councils of the villages under the TTCS project (Ishengoma *et al* 2016). The District, furthermore, identifies selling centers for charcoal produced in villages under the TTCS project, and collects taxes from the harvested forest products through the Village Council (Ishengoma *et al* 2016). Enhancing links between charcoal producers and members of their Village Council, District Council and potentially national governing bodies may assure the continuation of charcoal producer associations in the future. District officers revealed to us that they face challenges in terms of time limitations, understaffing and a lack of funding to carry out their tasks. This indicates the need for research on the limited interactions between the District and Village Councils to identify ways in which to (re)establish strong bonds between them.

#### *9.1.2.2 Conclusion on the effects of governance transitions on forest use*

In conclusion, **Chapter 6** and **Chapter 7** show that formal governance has the power to influence livelihoods and perceived access to forest resources (Fig. 9.1). This indicates that transitions to CBNRM may, at least partially, increase livelihood sustainability. Together with our finding that landscape-scale charcoal production patterns in villages under CBNRM differ significantly from those in villages under open access in **Chapter 5**, our studies reveal that formal governance can significantly influence charcoal production practices at local scale. This finding provides initial empirical evidence for the theoretical modelling exercise of **Chapter 3**, revealing the potential of transitions to alternative governance regimes to positively influence charcoal production activities and forests us. Yet, because we only assess livelihood capital access and forest use at one moment in time, we are, at present, unable to provide an indication on the long term sustainability of charcoal systems under open access and CBNRM. Although most charcoal producers appear positive about the CBNRM project implemented in their village, potential challenges in the continuation of formal institutions, such as charcoal producer associations and training schemes may threaten the continuation of dense social networks, as they are built on sporadic interactions. This could potentially result from dependence on TFCG to foster these formal schemes and may potentially threaten good governance of village forests, as dense social networks have been found to foster good governance (Grafton 2005, Hawkins and Maurer 2010, Musavengane and Kloppers 2020). Besides this trade-offs between income per bag and other livelihood capitals under CBNRM may force charcoal producers to produce more charcoal than indicated in their harvesting plan to assure that they can fulfill their basic needs. This may ultimately jeopardize the livelihood benefits individual charcoal producers and communities obtain under CBNRM through community development and forest management projects. Because charcoal producers often obtain income below the poverty line (Vollmer *et al* 2017), it is vital to better understand the potential trade-off between financial capital and other capitals, in order to identify mechanisms through which charcoal production outside of designated areas can be mitigated while compensating charcoal producers for the loss of income they receive per bag.

### 9.1.3 Effects of forest governance on charcoal production and forests

In **Chapter 8**, my co-authors and I studied global effects of forest governance and development on charcoal production and deforestation in the tropics. We define forest governance as the ways in which governing bodies, such as local and regional governments interact with each other to negotiate, make and enforce decisions regarding forest use and conservation. We define development as human wellbeing, reflected in Gross National Income (GNI) and the Human Development Index (HDI). We reveal that charcoal production in the tropics mainly correlates with development, resulting in a separation between countries from the African continent, which exhibit relatively high charcoal production and low development, and countries of the South American and Asian continents, which exhibit relatively low charcoal production and high development. Although this pattern has been described in literature, our empirical analysis visualizes the global patterns for the first time and shows that the separation between African and Asian and South American continents is even stronger than expected. Additionally, we, for the first time, show that governance, in terms of (i) its quality (as measured by World Governance Indicators), (ii) the number and types of governing bodies involved (e.g., governments and private companies), and (iii) the rights they have in governing forests (i.e., tenure and/or enforcement rights) has limited influence over charcoal production at a global scale. This is striking given the large investments made in forest governance to control forest use and to promote conservation (Arts and Vissen-Hamakers 2012, Arts 2014). Nevertheless, we find signs that tenure rights provisioning to regional governing bodies (e.g., districts or provinces) may influence governance outcomes in charcoal production systems by lowering production levels, potentially because they form a bridge between local and national governing bodies. We conclude that our study provides a first step into the identification of governance systems that effectively control charcoal production.

The results of **Chapter 8** put our local scale findings that governance has the power to influence livelihoods and forest use in charcoal production systems in perspective (see **Chapter 3** to **Chapter 7**). In particular, the study pinpoints towards the challenges countries face in fostering country-wide high quality forest governance, as well as in upscaling governance interventions that are effective locally, such as CBNRM (Figure 9.1). The reason for limited effects of formal governance on charcoal production likely relates to (i) the large role informal governance (i.e., societal norms) (Ashu 2016, Osei-Tutu *et al* 2015, Pacheco *et al* 2008) and (ii) widespread illegal charcoal production, as discussed in **Chapter 2** of this thesis. Hence, this thesis raises the question whether CBNRM of charcoal production can be further improved and effectively scaled up to foster sustainable charcoal producer livelihoods and forest use. At present only half of the conservation initiatives around the world are adopted by less than 30% of potential adopters (Mills *et al* 2019), which is partly related to a trade-off between the extent to which communities or people adopt a conservation initiative, such as CBNRM, and the speed at which it is adopted (Mills *et al* 2019). At present, CBNRM for charcoal production in Tanzania is mainly scaled up by an external party, TFCG, which aids local communities in applying for the required documents to manage their forests, provides training programs and initiates charcoal producer associations. Due to funding available from external parties, the project is being upscaled to villages within three districts in Tanzania at the time of study, namely Kilosa, Mvomero and Morogoro district (Ishengoma *et al* 2016). Although surrounding villages could theoretically implement similar projects themselves because the TTCS project harvesting scheme is in line with governmental rules for forest use on village land, it may be challenging for local communities to apply for the required documents and develop a harvesting plan themselves. This may indicate that continued external effort might be needed to upscale the CBNRM scheme further. It is important to upscale CBNRM over large continues areas, as we find indications in **Chapter 7** of this thesis that competition between open access and CBNRM regions occurs, which may challenge the attraction of intermediates to villages under CBNRM and the negotiation good prices for charcoal bags, which lowers the eventual price charcoal producers receive per bag. A resulting abolishment of charcoal production or a shift towards illegal production in villages under CBNRM may reduce income from taxes through the revenue-sharing scheme, ultimately jeopardizing the forest management and community development initiatives in place.

#### *9.1.3.1 Effects of forest governance on charcoal production in context of Ostrom's design principles*

The design principles for sustainable management of the commons were derived based on data and observations derived at local scale (Mcginnis and Ostrom 1992). Even though the principles are considered to be transferable to local settings all around the world, question remains what role they play at large scales, especially global scales, where many different governance systems apply under a wide range of social-ecological conditions (Stern 2011). This makes it difficult to provide a meaningful discussion on the findings of **Chapter 8** in light of the eight design principles of Ostrom. Future studies on effects of governance on charcoal production may evaluate the extent to which design principles are met in tropical countries around the world. For instance, studies could derive a gradient of adherence to each design principle per country based on the existing governance system in place, preferably including informal governance systems. For example, the different types of forest governance in local communities within countries and the extent to which they govern a countries' total (forest) area (e.g., open access and communal management governance types in Tanzania) could be determined. If quantified, this information would potentially allow for an assessment of this information together with the data analyzed in **Chapter 8** to determine the potential role of the eight design principles of Elinor Ostrom in shaping charcoal production, deforestation, governance and development at global scales.

### 9.1.4 Limitations and opportunities for future studies

In this thesis, I, together with my co-authors, aimed to provide a comprehensive overview of the effect of transitions, in particular governance transitions, in charcoal production systems on forests and livelihoods. We used the social-ecological systems framework and Ostrom's design principles to organize our findings. Although this thesis provides important novel insights into the majority of primary social-ecological system components and explores several of their interactions, there are limitations to the extent to which we can answer our main research question.

First, it proved challenging to empirically determine direct effects of charcoal production system transitions on forest use and charcoal producer livelihoods. The empirical studies of **Chapter 5**, **Chapter 6** and **Chapter 7** rely on counterfactual analyses, for which we compared one baseline resource system (i.e., villages under open access) with one resource system in which a specific governance intervention was implemented (i.e., villages under CBNRM). We adopted this approach because we were unable to go back in time in villages under CBNRM to compare livelihoods and forest use before and after CBNRM. Hence, our studies did not provide a direct indication of effects of governance transitions on forest use and livelihoods. Rather, our counterfactual analysis informs us about the potential implications such transition may have. These means that the results of our study are influenced by local circumstances and complementary projects, such as projects that aim to promote sustainable agriculture. We largely avoided interference of other projects because we selected villages that did not have a project in place to manage their forest land before and during the TTCS project. Besides this, the comparable results for the three villages under CBNRM and the three under open access, as well as significant differences between the two village types indicate consistent effects of governance, despite differentiations in local circumstances in the villages. Finally, sensitivity analyses reveal robust differentiations between the two village types. Therefore, we believe that our empirical studies provide a robust indication of the impact of charcoal system transitions on forest use and livelihoods.

Second, we faced challenges in the direct assessment of interactions and relationships between the different social-ecological components of charcoal production systems. Although we wished to assess interactions between charcoal livelihoods and forest resources, we were unable to directly link our livelihood survey results of **Chapter 6** and **Chapter 7** to the remote sensing results of **Chapter 4** and **Chapter 5**. Therefore, we could not directly link the production activities of charcoal producers across the landscape with the access they have to livelihood capitals. Instead, we relied on perceptions of charcoal producers on the sustainability of their practices to reflect upon potential interactions between social networks, knowledge and forest resource use. This prevented us from providing explicit evidence on effects of social networks and access of charcoal producers to other livelihood capitals on forest use. Nevertheless, by reflecting on our findings in light of social-ecological system theory and the design principles of Elinor Ostrom, we were able to differentiate potential effects of access to and trade-offs between livelihood capitals on forest use. It also allowed us to reflect on the mismatches we observe between governance goals and reality with regard to production outside designated areas. Vice versa, our assessment of charcoal production patterns and forest aboveground biomass allowed us to identify potential causes for the trade-offs and synergies we observed between livelihood capitals.

Third, we faced issues of scale in both spatial and temporal domains. Although **Chapter 8** puts the local findings of **Chapter 4**, **Chapter 5**, **Chapter 6** and **Chapter 7** in perspective, we are unable to distinguish the exact effects local scale governance initiatives have on charcoal production on a country or worldwide scale. To get a better idea of such implications studies, at regional scale and continental scale are necessary to bridge the gap between local and global. Based on the studies in this thesis, we can identify multiple roads that could be taken to bridge local and global studies. For instance, the analysis of **Chapter 8** could be repeated at continental scales (i.e., an assessment of governance and development effects on charcoal production for the African, South American and Asian continents separately). Besides this, the governance typology developed for **Chapter 8** could be expanded, e.g., by including the decision-making process in place, the funding each governing body receives, the way it is spend, and the specific tasks governing bodies have, as well as their manpower. Such study would provide a more detailed overview of forest governance per tropical country, which may allow for a more exhaustive assessment of the key ingredients necessary for good forest governance. Additionally, the analyses of **Chapter 4**, **Chapter 5**, **Chapter 6**, and **Chapter 7** could be repeated on a regional scale, e.g., covering the entire Kilosa District. The studies of **Chapter 4** and **Chapter 5** could be relatively easily repeated in other parts of the world because they are based on satellite imagery that is globally available. For this purpose, citizen science projects could be carried out to acquire GIS locations on kilns or kiln scars. Despite mismatches in scale between our local and global studies, the different approaches used in this thesis and scales of analyses allowed us to provide a comprehensive overview of the extent to which governance can shape forest use and livelihoods.

Fourth, it was challenging to empirically assess the sustainability of transitions in charcoal production systems on livelihoods and, in particular, forest use because all studies, apart from **Chapter 3**, provide a snapshot in time. To provide an indication of the sustainability of livelihoods and forest use, our stylized model of **Chapter 3** could be expanded and parameterized with the livelihood data and forest use data we acquired in our study area to extrapolate our empirical findings over time, e.g., using multiple scenarios. This would allow us to test our theoretical expectations of long term transitions in charcoal production systems. Besides this, repeating the studies of **Chapter 5**, **Chapter 6** and **Chapter 7** in the same area would allow for an assessment of variability in forest use and livelihood capital access and their synergies and trade-offs. The method developed in **Chapter 4** may have potential to predict charcoal sites over time, allowing for a study of past forest use for charcoal production. Identifying charcoal sites from the past would allow scientists and practitioners to track forest biomass and biodiversity regeneration (e.g., by assessing forest biomass and biodiversity in charcoal sites created in the year 2014 to 2020). Such assessment requires a thorough testing of the temporal performance of the remote sensing method developed in **Chapter 4**, which requires additional field studies to document charcoal kilns, their scars and harvesting areas created in different years. This field data may then be compared to remotely-sensed charcoal sites of different years based on the random forest models developed for the year 2019. Once the performance of the random forest models has been established, limited further fieldwork is necessary to assess charcoal production over time, as the model may be fueled with satellite data of different years, and complemented by visually inspected charcoal sites for these respective years. Thus, even though the studies in this thesis only provide a snapshot in time, they have great potential to be used in spatial-temporal modelling and remote sensing analyses in the future to assess and predict the temporal sustainability of forest use and livelihoods in charcoal systems.

Finally, we faced challenges in determining causations for results we obtained, in particular in our livelihood assessments of **Chapter 7** and our assessment of drivers behind charcoal site patterns in **Chapter 5**. Although the directionality of the correlations between livelihood capital indicators are clear in **Chapter 7**, revealing synergies or trade-offs between them, the cause for these synergies and trade-offs remains up to interpretation. In the discussion of **Chapter 7**, we have touched upon the many explanations there are for the synergies and trade-offs we find, often highlighting that one livelihood indicator may cause an increase or decrease in another indicator or the other way around. For instance, we find that social interactions may enhance income derived from charcoal production or vice versa but the exact causation of this synergy remains unclear. Additionally, we only use a selection of indicators per capital and many more relevant indicators could be used to assess charcoal livelihoods. An expansion of indicators may provide further or different explanations for our current findings and may be used to identify causes and consequences of livelihood capital interactions. Additionally, in depth interviews and focus groups may further reveal the story behind our quantitative results. Overall, any further assessment of charcoal producer livelihoods may be informed by our current study, e.g., by identifying trade-offs and synergies that require further exploration to understand causalities.

## 9.2 Opportunities and challenges in social-ecological system science

I find that the social-ecological systems framework of Ostrom and the eight design principles are useful tools to organize and communicate the interdisciplinary research I have conducted in this thesis. While the social-ecological systems framework allowed me to think about relationships between the different primary components I investigate in this thesis, the eight design principles enabled me to explore reasons behind both the matches and mismatches between governance goals and reality we find. This process automatically guided me to emerging knowledge gaps and aided me to formulate hypotheses on them. The simplicity of the social-ecological systems concept allows for flexibility in thinking. Hence, both the social-ecological systems framework and the design principles of Elinor Ostrom function well as organizational tools to identify potential causations. For example, a reflection on our results in light of design principles, such as clarity of boundaries, the congruence of rules for forest use to local circumstances and forest monitoring, allowed me to identify potential causes for mismatches between governance goals and reality that could be explored further in future studies. This also allowed my co-authors and I to identify potential aspects of current CBNRM projects that could be further improved (see Section 9.3).

Nevertheless, I found that the social-ecological systems framework does not function well as a guide to align methodologies of different Chapters to assure that the results obtained in them can be effectively related or compared. I found that challenges in aligning methodologies to assess relationships between social-ecological systems components mainly result from differences in spatial scale between the different types of data gathered. For instance, I was unable to directly relate the findings of **Chapter 5** with those of **Chapter 6** and **Chapter 7**, even though they both reveal charcoal producer behavior. This, because the findings of **Chapter 5** were based on spatial data, while the findings of **Chapter 6** and **Chapter 7** were based on non-spatial data. This points to a challenge that was not identified by Partelow (2018) (see Section 1.3.1), namely the challenge of relating indicators of different primary components of the social-ecological systems framework to assess their relationships within the same study system. This experience suggests that methodological gaps do not only exist when comparing findings on similar components between different studies but also when relating findings of different social-ecological system components directly. Issues of scale are not new to social-ecological system science (Cumming *et al* 2006), and this thesis further emphasizes its role in developing a cohesive approach based on a range of methods origination from varying disciplines to provide a holistic overview of social-ecological system dynamics. Introducing a component of scale in the social-ecological systems framework may function as a reminder that issues of scale may arise when assessing direct relationships between social-ecologcial systems components. It may also point out the spatial and/or temporal scale at which the different compontens are usually assessed or should ideally be analyzed.

Interestingly, I believe that I could have potentially directly related the findings of **Chapter 5** with those of **Chapter 6** and **Chapter 7**, if I would have paid more attention to the spatial scales at which I obtained results on forest use and livelihoods. This would have allowed me to align them. For example, I could have gathered spatial information on the locations where interviewed charcoal producers live. This would have allowed me to link their livelihoods with forest biomass availability and charcoal production patterns that occur in their vicinity, enabling me to partially overcome the data transformation gap we faced. Yet, if such approach is adopted in the future, it should be carefully constructed to prevent the violation of charcoal producer privacy, to prevent risk of prosecution for illegal production, and to assure the anonymity of interviewees.

## 9.3 Recommendations for scientists, practitioners and policy makers

Biomass-based renewable energies, such as charcoal, have the potential to be carbon neutral or even carbon positive. If we would like to produce charcoal sustainably, we need to foster transitions that allow for a continuation of charcoal production, even under high demands, without degrading or depleting the woody biomass resources from which charcoal is produced. In this thesis, I have presented evidence of governance impacts on forest use and livelihoods. I show that, in theory, governance transitions to communal management and private systems have the potential to foster sustainability. Yet, in reality, I find both matches and mismatches between governance goals and outcomes, and reveal that governance is less important than social-economic drivers at a global scale. These findings indicate that more research is needed to identify conditions under which existing governance systems, such as communal management systems, may function best to allow policy makers and practitioners to improve them. Simultaneously, I would recommend to adopt a flexible approach in implementing policies to assure that they can be adjusted over time to local circumstances based on new knowledge on conditions under which policies can best be implemented, such as those present herein, as principles of adaptive management suggest. Such adaptive changes could mitigate the trade-off between income per bag and the remaining capitals, to assure a continuation of CBNRM that provides livelihood benefits for both individual charcoal producers and whole communities. Governments may also test whether specific rules implemented at a national scale, such as defining strict forest boundaries and designated areas for production, suit local circumstances and vice versa. For instance, it may be useful to identify ways in which local (informal) governance could be integrated in regional and national goals. This requires a cross-scale analysis of trade-offs between different policy interventions at different spatiotemporal scales. On the long term, such investments may mitigate production that is not in line with implemented harvesting plans and/or with existing forest laws.

In our study system in Tanzania, I would recommend policy makers and practitioners to assure the continuation of formal institutions that foster collaboration between charcoal producers and interactions with members of their village government, as previous studies show that this can promote trust, adaptive capacity and eventually good forest governance. To do so, policy makers and practitioners may first assess the reasons behind the discontinuation of charcoal producer associations. This may provide insights into the ways in which the sustainability of formal institutions, such as harvesting plans may be enhanced to assure their continuation. For instance, mechanisms may be identified that foster stronger incentives for local and regional governments and charcoal producers to continue charcoal producer associations, training schemes and participatory harvesting, independent from third parties. In particular, attention could be paid to further fostering of functional nested governance regimes, allowing local governments, district governments and potentially national governments to interact as specified in CBNRM harvesting plans and in accordance to the forest laws and by-laws of Tanzania. Our qualitative results suggest that particular attention could be paid to the provisioning of sufficient funding and manpower to District Councils.

Overall, I would recommend two studies that may aid in the identification of the origin of matches and mismatches between CBNRM goals and reality. First, it is important to understand the reasons behind charcoal production outside of designated areas observed in **Chapter 5**. For example, the potential influence of clear boundaries could be explored. This may be achieved through surveys on (i) the awareness of charcoal producers on the boundaries of designated areas and their village forest land in general, (ii) the ways in which they communicated with each other about these boundaries, and (iii) the manner in which the Village Council shares this information. Additionally, scientists and practitioners may assess what type of knowledge is exchanged during charcoal producer association meetings and training schemes. They may promote knowledge sharing about harvesting locations and good governance among charcoal producers, not only among Village Council members. A study could be conducted to identify ways in which transitions could be fostered from CBNRM dependent on external actors to CBNRM based on internalized and nested governance to assure that communities can independently continue communal forest management on the long term. Challenges communities face in monitoring could be explored to put these findings into perspective and a focus group may shed light on the general opinion of charcoal producers and members of their village government on a designated forest area and boundaries. This may allow policy makers and practitioners to further adjust their CBNRM scheme to local circumstances over time. Second, it is vital to understand effects of charcoal production patterns on forest biomass and biodiversity. For instance, a field study on forest biomass and biodiversity in the forests of villages under CBNRM could be carried out to better understand ecological implications of governance effects on charcoal site sizes, shapes and distributions observed in **Chapter 5**. Such research may provide insides into the ways in which the size of designated areas for charcoal production and general rules and regulations on harvesting may be adjusted. Potentially, selective cutting in smaller and more regularly shaped sites under CBNRM promotes forest regeneration and prevents biodiversity loss, limiting the environmental impact of charcoal production outside of designated areas. However, it might also be the case that small and regularly shaped sites create fragmentation, and that production in a designated forest area, while protecting the remaining forest area is preferable. In this case, it is vital to enhance charcoal producer adherence to existing harvesting plans.

## 9.4 Brief reflection on the scope and depth of the thesis

Unlike the majority of PhD projects, this PhD thesis provides a broad overview of the charcoal system as a social-ecological system, rather than an in-depth assessment of a specific component of charcoal production systems or a particular relationship that occurs in them. Like in-depth assessments, a broad overview has both advantages and limitations. The main advantage of the interdisciplinary approach adopted in this thesis is that it allows for an overall better understanding of the charcoal system as a whole. By combining observational data acquired through remote sensing, perceptions of charcoal producers on the sustainability of their forest use and a range of social-economic data, I was able to raise new questions that might otherwise not have been raised. For example, I was able to raise specific questions regarding the effectiveness of CBNRM and potential reasons for matches and mismatches between policy goals and reality. I was also able to showcase the limitations of the approach adopted for a Chapter in light of results from other Chapters. For instance, if I had only assessed forest use through satellite imagery and concluded that this was not entirely in line with the CBNRM harvesting plan in place, I might have hinted that forest use in the CBNRM villages is most likely unsustainable. In this case, I would not have been able to raise a discussion on forest use in light of our livelihood data that showcases largely positive views of charcoal producers on the sustainability of their forests in villages under CBNRM. This example shows that environmental data greatly complements social data and vice versa, and that there is an added value of collecting both in one PhD project to derive a more holistic understanding of social-ecological systems.

Yet, this thesis also reveals limitations in terms of the conclusions that it can derive based on the broad studies that were conducted. These mainly result from time limitations and limitations in resources, skills and experience. For instance, it may have been possible to collect data that provides a more in-depth insight in the sustainability of forest use over time. Addtionally, more villages could have been explored, increasing the sample size to such a level that a correlation between average forest availability, forest use for charcoal production and livelihoods capitals could be directly derived. This could have allowed us to better understand the relationship between perceived forest sustainability and forest use. Based on this brief reflection, I believe it is important that both in-depth and broad-scale assessments continue to be conducted, preferably in a systematic manner that allows for a direct use of data from one study in another study. A recent study suggests that we may learn from ecological experiments, such as the Jena experiment, to collect data on all social-ecological system components in a systematic manner and organize it in open access databases (Cumming *et al* 2020). In order for broad scale assessments to be conducted in more depth within the current academic system, I would suggest to create intensively collaborating teams of PhD students, each tackling in-depth questions on one or a limited number of components of social-ecological systems. This process needs to be highly coordinated to be able to derive conclusions from combined findings, and it would need an extensive understanding of the approaches and findings of all projects by all fellow PhD team members. For this purpose, PhD students could develop the approaches and methodologies althogether and have multiple feedback sessions to discuss results, combining them together during workshops to get to new insights and identify new questions, e.g., in light of the eight design principles of sustainable commons management of Elinor Ostrom as examplified in this thesis.

## 9.5 Conclusion

In conclusion, this thesis sheds light upon impacts of transitions in charcoal production systems on forest use and charcoal producer livelihoods through an exploration of different social and ecological components of charcoal production systems in the tropics, their interactions and their response to interventions that aim to initiate sustainability transitions. In particular, my co-authors and I hypothesize that transitions in governance from open access systems to communal management and private systems have the potential to mitigate charcoal-related deforestation and forest degradation, while allows for a continuation of charcoal production, which benefits livelihoods. In line with our hypotheses, our stylized modelling exercise of **Chapter 3** shows that transitions to low demand, alternative energies (e.g., gas) and effective governance enhance forest resource availability. Yet, we show that such transitions only mitigate deforestation and forest degradation sufficiently at low demand and that governance transitions are necessary to communal or private systems to mitigate a collapse of forest resources and subsequent collapse of charcoal production at high demand. In **Chapter 4** to **Chapter 7** local counterfactual empirical analyses in six study villages in Kilosa District of Tanzania informs us about actual effects of governance transitions from open access systems to communal management on forest use and livelihoods. In line with our hypothesis, these studies reveal that forest governance transitions have the potential to alter forest use for charcoal production and the access charcoal producers have to livelihood resources; hence, their livelihood sustainability. Yet, we find mismatches between governance goals and reality in communal management systems and trade-offs between livelihood capitals. Through a reflection of our results in perspective of the design principles for sustainable management of commons by Elinor Ostrom we identified potential reasons for mismatches between governance goals and reality. These include a potential discontinuation of formal institutions for shared decision-making, such as charcoal producer associations, a trade-off between aspects of financial capital and other livelihood resources, and a shortage of forest resources to produce charcoal from. We put our local results in perspective in **Chapter 8** through a global study on the impacts of governance on charcoal production and deforestation. In line with our hypothesis, we show large effects of development and minimal effects of governance. Altogether our empirical results reveal challenges in the percolation of governance goals from national to local scale and vice versa, indicating the need to create a bridge that allows for the upscaling of effective governance schemes for charcoal production, while simultaneously enhancing the efficiency and effectiveness of governance regimes implemented at national scale. Overall, our results highlight the complexity of fostering access to all livelihood capitals needed to pursue a sustainable livelihoods, while simultaneously fostering effective management of forest use. Future research may further relate livelihood capital synergies and trade-offs to charcoal site patterns in the landscape to further enhance our understanding of relationships between social and ecological system variables. This may ultimately further advance existing governance regimes and may allow policy makers and practitioners to upscale sustainable ones to foster wide-scale transitions in charcoal production systems that promote forest and livelihood sustainability.

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# Appendices

## Appendix Chapter 3

### Supplementary materials A

In these Supplementary materials, we provide an overview of the model parameterization and the rationale behind this parameterization. The parameterization can be found in Table A.1. We conducted a literature review to determine values for the parameters in the model. If the literature reported values across a range, we used the average of this range.

### 1. Initial parameter settings

As shown in the main text, we modelled forest biomass, plantation biomass, and charcoal biomass over time as follows:

$$\frac{dB_f}{dt} = G - H \qquad \text{(A.1)}$$

$$\frac{dB_c}{dt} = cH - (\delta_p + n)B_c \qquad \text{(A.2)}$$

, where $t$ is time (years), $c$ is carbonization efficiency of forest biomass into charcoal, $\delta p$ the depreciation rate of charcoal (year$^{-1}$) (e.g. reduction in amount due to consumption), and n the per capita human population growth rate (year$^{-1}$).

We assumed an average depreciation rate of 0.5, often used for charcoal biomass (Nadiri and Prucha 1993). We assumed a population growth rate between 1.1% (the global average) and 2.7% (the predicted average population growth rate in Africa) (WEF 2017). The majority of charcoal worldwide is produced in relatively low efficiency earth mounds, whose efficiency ranges between 0.08 and 0.30 (FAO 2017). Therefore, we assumed an average efficiency of 19%, which is also used as an average by Chidumayo (2013). The carbonization efficiency can, however, increase up to 60% (FAO 2017). As initial forest level, we assumed a forest stock of 449,500 Mg, which is the lowest maximal forest stock in our modelling area (see section 2 of these Supplementary Materials). For private plantations we assumed that 100% of the total plantation biomass is available at the start of the simulations at the lowest maximal plantation biomass, which equals 367,600 Mg (see section 2). We assumed that initially 1,260 Mg of charcoal is available in the system.

We used a carbonization efficiency of 19% (the rational for this is explained in *Section 1* of this Supplementary materials) (Chidumayo 2013). For the sensitivity analyses, we assessed the effect of a certain parameter on the overall dynamics of the model by simulating an increase in the value of this parameter within the range set in Table A.1.

### 2. Woody biomass accumulation in forests and plantations

As shown in the main text, we modelled woody biomass accumulation in forests and plantations as follows:

$$G = gB_f(1 - \left(\frac{B_f}{K}\right)) \qquad \text{(A.3)}$$

, where $G$ is the growth in forest or plantation biomass (Mg.year$^{-1}$), $g$ the growth rate of forest or plantation biomass (year$^{-1}$), $B_f$ is forest or plantation biomass (Mg.year$^{-1}$), $K$ the carrying capacity of forest or plantation biomass (Mg).

We modelled the feedback between forest biomass and charcoal biomass over time steps of exactly 1 year in a representative area of 10,000 ha. Of these 10,000 ha, we assumed that 5,000 ha contains tropical forest. We chose to model within a forest area of 5,000 ha because this area contains enough woody biomass for multiple people to produce charcoal at the same time (Ishengoma *et al* 2016, Woollen *et al* 2016).

Maximal tropical forest biomass accumulation levels around the world range from 89.9 Mg.ha$^{-1}$ in subtropical dry forests to 689.7 Mg.ha$^{-1}$ in tropical premontane wet forest (Brown and Lugo 1984). Therefore, the forest of 5,000 ha, can harbor maximal tropical forest biomass levels between 89.9*5,000 = 449,500 – 689.7*5,000 = 3,448,500 Mg. Biomass accumulation levels of tropical forests range between 0.57 – 7.50 Mg.ha$^{-1}$.year$^{-1}$, with high forest biomass accumulation in tropical wet forests and low biomass accumulation in tropical dry forests (Hofstad and Araya 2015, Bonner *et al* 2013). This equaled 5,700 – 75,000 Mg.year$^{-1}$ within our modelling area of 10,000 ha. Depending on the maximal forest biomass level, growth rates of forest biomass ranged between (5,700 / 899,000)*100% = 0.63% and (75,000 / 6,897,000)*100% = 1.09% per year.

For private systems, we assumed plantations that solely contain *Eucalyptus* trees, which is the most common species in charcoal plantations (Morello 2015, Lejeune *et al* 2013). The maximal biomass of *Eucalyptus diversicolor* stands ranges between 183.8 – 232.2 Mg.ha$^{-1}$ (Grierson and Adams 1999). We assumed that 20% (2,000 ha) of the modelling area is covered with plantations at the start of our simulation. Hence, the maximal biomass value of plantation systems ranged between 2,000*183.8 = 367,600 Mg and 2,000*232.2 = 464,400 Mg. *Eucalyptus* plantation growth rates ranged between 5.6 and 12.7 Mg.ha$^{-1}$.year$^{-1}$, which equaled 56,000 – 127,000 Mg.year$^{-1}$ within our modelling area (Guo *et al* 2002, Grierson and Adams 1999). Depending on the maximal biomass levels of *Eucalyptus* plantations, growth rates ranged between (56,000/1,838,000)*100% = 3.04%, and (127,000/2,322,000)*100% = 5.47%.

## 3. Charcoal production capacity

As shown in the main text, we modelled charcoal production capacity, defined as the maximal amount of charcoal that is economically viable to harvest, as follows:

$$P = \frac{DB_f^2}{(v^2+B_f^2)} - \frac{B_c}{q} \qquad (A.4)$$

, where $P$ is the production capacity of charcoal (Mg.year$^{-1}$), $D$ is the demand (Mg.year$^{-1}$) and $v$ is the forest biomass level at which half of the maximal demand is reached (Mg), $q$ is time (year). For systems in which charcoal is produced from plantations, production capacity does not depend on forest biomass but rather on the amount of available plantation biomass.

We assumed that our modelling area is subjected to a demand of 10 – 100,000 Mg.year$^{-1}$ (the average consumption of charcoal per country in 2016 was 823,000 Mg (UN 2019)). We estimated the point of decrease in charcoal production capacity ($K$) based on empirical observations of charcoal production in systems under varying levels of demand and tropical forest levels (Baumert *et al* 2016, Schaafsma *et al* 2012, Woollen *et al* 2016). Woollen *et al.* (2016) showed that areas in which a relatively low charcoal production was observed despite high levels of demand, contained ±60% to ±85% forest cover. The area with ±60% forest contained of which 25% Mopane (11.8 Mg/ha), 10% Combretum (12.8 Mg.ha$^{-1}$) and 25% Boscia (5.4 Mg.ha$^{-1}$) forest, which equaled an average forest biomass level of 9.3 Mg.ha$^{-1}$ (Woollen et al. 2016). The area with ±85% forest contained 50% Mopane (11.8 Mg.ha$^{-1}$), 25% Combretum (12.8 Mg.ha$^{-1}$) and 10% Boscia (5.4 Mg.ha$^{-1}$) forest, which equaled an average forest biomass level of 11.3 Mg.ha$^{-1}$ (Woollen *et al* 2016). Therefore, we assumed that the point that half of the maximal charcoal capacity is reached occurs between tropical forest biomass levels of 0.6*10,000*9.3 = 55,800 Mg and 0.8*10,000*11.3 = 90,400 Mg.

## 4. Forest and plantation harvesting

As shown in the main text, we modelled wood harvesting for charcoal production as follows:

$$H = \frac{mP^2}{(x^2+P^2)} \qquad (A.5)$$

$$H_p = \frac{m_p B_f (D-\frac{B_C}{q})^2}{(x^2+D^2)} \qquad \text{(A.6)}$$

, where $H$ is the forest biomass harvested in open access systems (Mg.year$^{-1}$), $m$ the maximal forest biomass that can be harvested (Mg), $x$ the production capacity / demand level at which half of the maximal harvest is reached (Mg), $Hc$ the wood harvested in communal management systems (Mg.year$^{-1}$), $m_c$ the harvesting rate in communal management system (year$^{-1}$), $m_p$ the harvesting rate in private systems(year$^{-1}$), $Hp$ the plantation biomass harvested in private management systems (Mg.year$^{-1}$).

For open access, we assumed a population of 100 charcoal producers in the area. This is a realistic number of producers as Baumert *et al.* (2016) observed between 65 and 92 households producing charcoal per village in rural Mozambique, which has a rural population density of 1000 people per 10,000 ha or lower (WB 2012). We assumed a plausible range of charcoal production in open access systems of 7,770 – 231,000 kg per producer year (Baumert *et al* 2016, FAO 1983). Producers in the lower range are rural part-time producers (< 9,590 kg), of which maximal harvest per year was calculated by multiplying the number of charcoal sacks per year with the weight of 70 kg per sack (Baumert *et al* 2016). We assumed that producers that produce more than 9,590 kg per year are full-time producers (FAO 1983). We base this on an FAO report that indicates that 924 tons per year is produced by a 4 man crew. With an average conversion rate of wood to charcoal of 19% in earth-mound kilns for rural areas and 43% for Brazilian migratory producers (FAO 2017), the maximal harvest of producers ranged between 40,895 – 537,209 kg wood per year. With an average amount of charcoal producers of 100, this resulted in a minimal harvesting rate of 4,089,500 kg and a maximal harvesting rate of 53,720,900 kg.

For communal management systems, we assumed a harvesting rate of 0.009, which allows for forest regeneration over time and prevents forest depletion. We use this rate because the aim of communal management is to foster a continuation of both forest and charcoal biomass production over time through rules and regulations (Ishengoma *et al* 2016). For private systems, we assumed that enough producers are available to harvest plantation biomass at a level that sustains plantation biomass levels over time. At the average growth rate of plantation biomass of 0.0426 (Grierson and Adams 1999, Guo *et al* 2002) (Grierson and Adams 1999; Guo, Sims, and Horne 2002), we assumed a harvesting rate of 0.043, which allows plantation biomass to regenerate so that a constant supply of plantation wood is fostered. Finally, we assumed that for all systems the point of half the maximal harvesting rate (x) equals 25% of the maximally produced charcoal per year.

**Table A1.** Model parameters, definitions and value ranges based on literature. See the content of ***Supplementary materials A*** for an argumentation of each parameter range/value.

| **Parameter** | **Parameter definition** | **Range** | **Value** |
|---|---|---|---|
| $B_f$ *(initial value)* | Tropical forest and plantation biomass (Mg) | *Forest*: 449,500 - 3,448,500 Mg (Brown and Lugo 1984)<br>*Plantation*: 367,600 – 464,400 Mg (Lejeune *et al* 2013, Grierson and Adams 1999) | *Forest*: 449,500 Mg<br>*Plantation*: 367,600 Mg |
| $B_c$ *(initial value)* | Charcoal biomass (Mg) | | 1,260 Mg |
| $m$ | Maximal wood harvest per year in open access systems (Mg.year$^{-1}$) | 4,090 - 53,721 Mg.year$^{-1}$ | 28,906 Mg.year$^{-1}$ |
| $m_c$ | Harvesting rate in communal management systems (year$^{-1}$) | | *Communal*: 0.009 year$^{-1}$ |
| $m_p$ | Harvesting rate in private systems (year$^{-1}$) | | *Private*: 0.043 year$^{-1}$ |
| $D$ | Maximal demand (Mg.year$^{-1}$) | 10 – 100,000 Mg.year$^{-1}$ | |
| $v$ | The point at which half of the maximal charcoal carrying capacity is reached (Mg.year$^{-1}$) | 55,800 - 90,400 Mg.year$^{-1}$ (Woollen *et al* 2016) | 73,100 Mg.year$^{-1}$ |

| | | | |
|---|---|---|---|
| $g$ | Growth rate of tropical forest and plantation biomass ($year^{-1}$) | *Forest*: 0.0063 – 0.0109 $year^{-1}$ (Hofstad 1997, Bonner *et al* 2013)<br>*Plantation*: 0.0304 – 0.0547 $year^{-1}$ (Grierson and Adams 1999, Guo *et al* 2002) | *Forest*: 0.0086 $year^{-1}$<br>*Plantation*: 0.0426 $year^{-1}$ |
| $x$ | Point at which half of the maximal harvest is reached ($Mg.year^{-1}$) | 2,072 – 2,961 $Mg.year^{-1}$ | 2,517 $Mg.year^{-1}$ |
| $K$ | Carrying capacity of forest and plantation biomass (Mg) | *Forest*: 449,500 – 3,448,500 Mg (Hofstad and Araya 2015)<br>*Plantation*: 367,600 - 464,400 Mg (Grierson and Adams 1999, Guo *et al* 2002) | *Forest*: 1,949,000 Mg<br>*Plantation*: 416,000 Mg |
| $c$ | Carbonization efficiency of earth-mound kilns | 0.08 – 0.60 $year^{-1}$ (FAO 2017) | 0.19* $year^{-1}$ |
| $\delta_p$ | Depreciation rate of charcoal production ($year^{-1}$) | 0.5 (Nadiri and Prucha 1993) | |
| $n$ | Population growth rate ($year^{-1}$) | 0.011 – 0.027 $year^{-1}$ (WEF 2017) | 0.019 $year^{-1}$ |
| $q$ | Time | | 1 year |
| * Rather that the average this number refers to the most common carbonization efficiency of kilns used in the tropics (FAO 2017). | | | |

## Supplementary materials B

In this Supplementary Materials, we show the model results for variations in demand over time, the impact of a transition after 500 years, the impact of changes in conversion efficiency at high levels of demand (60,000 Mg.year$^{-1}$, and the impact of a demand reduction of 100 Mg.year$^{-1}$ and 50 Mg.year$^{-1}$. The figure captions describe the how to read the figures.

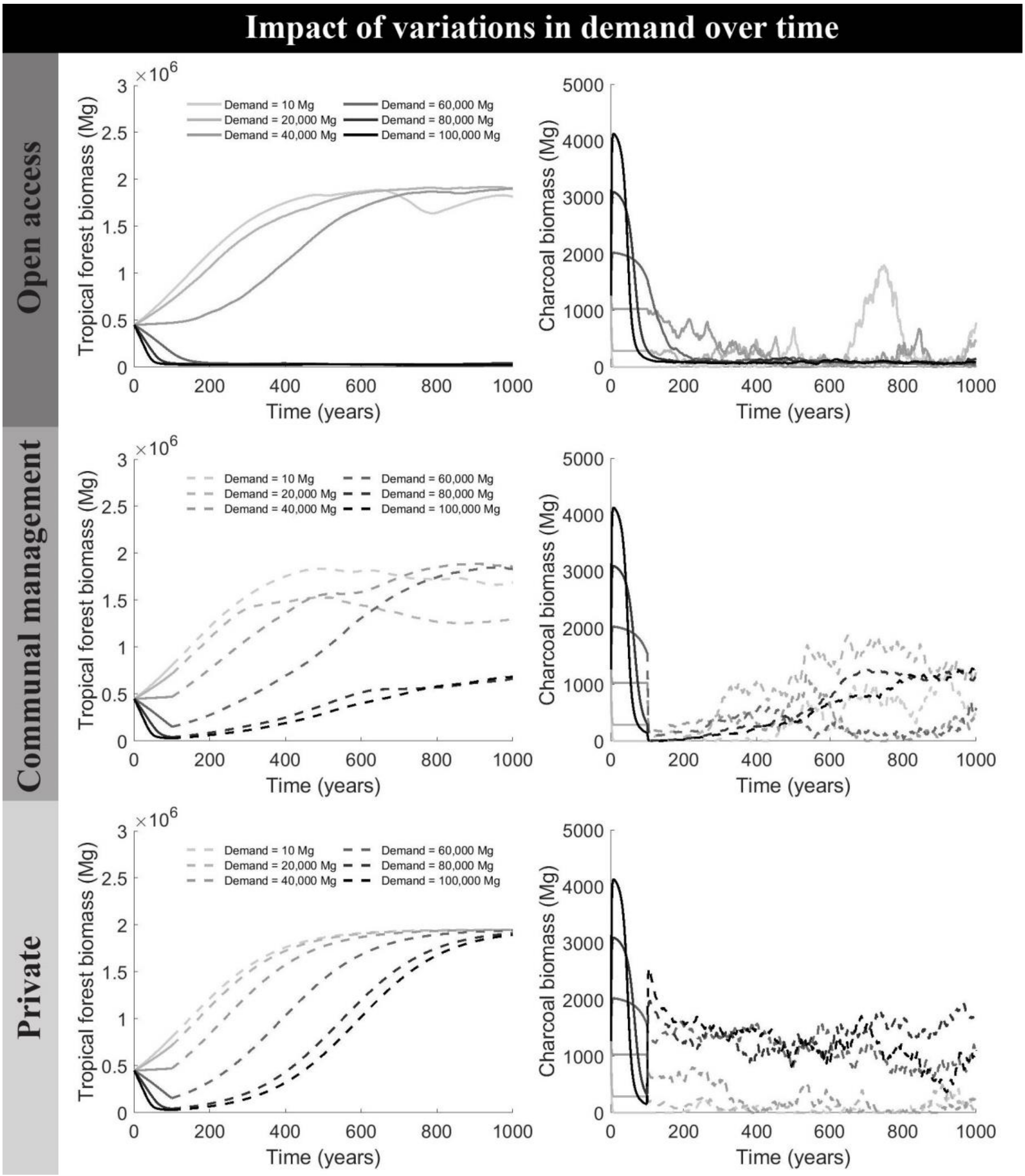


**Figure B1.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of demand (10 to 100,000 Mg.year$^{-1}$ in steps of 10,000 Mg). Every line indicates a certain level of demand (see legends). The level of demand is indicated by different gray tones, from light gray for low demands to black for high demands. We simulated random changes between -1000 and 1000 Mg.year$^{-1}$ in demand levels over time. A transition from an initially open access system after 20 years is simulated for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

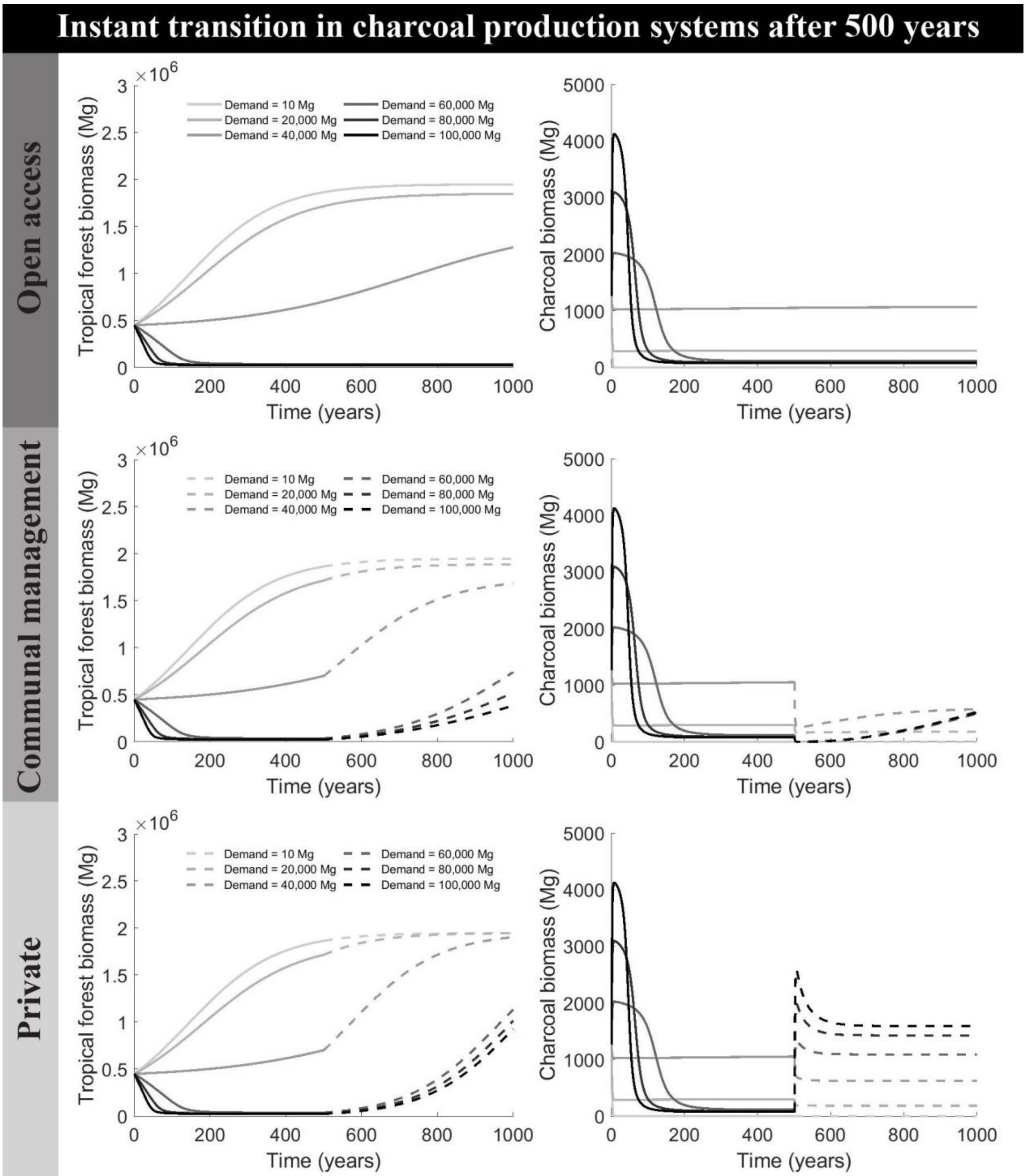


**Figure B2.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of demand (10 to 100,000 Mg.year$^{-1}$ in steps of 10,000 Mg). Every line indicates a certain level of demand (see legends). The level of demand is indicated by different gray tones, from light gray for low demands to black for high demands. **A transition from an initially open access system after 500 years is simulated for every level of demand.** The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

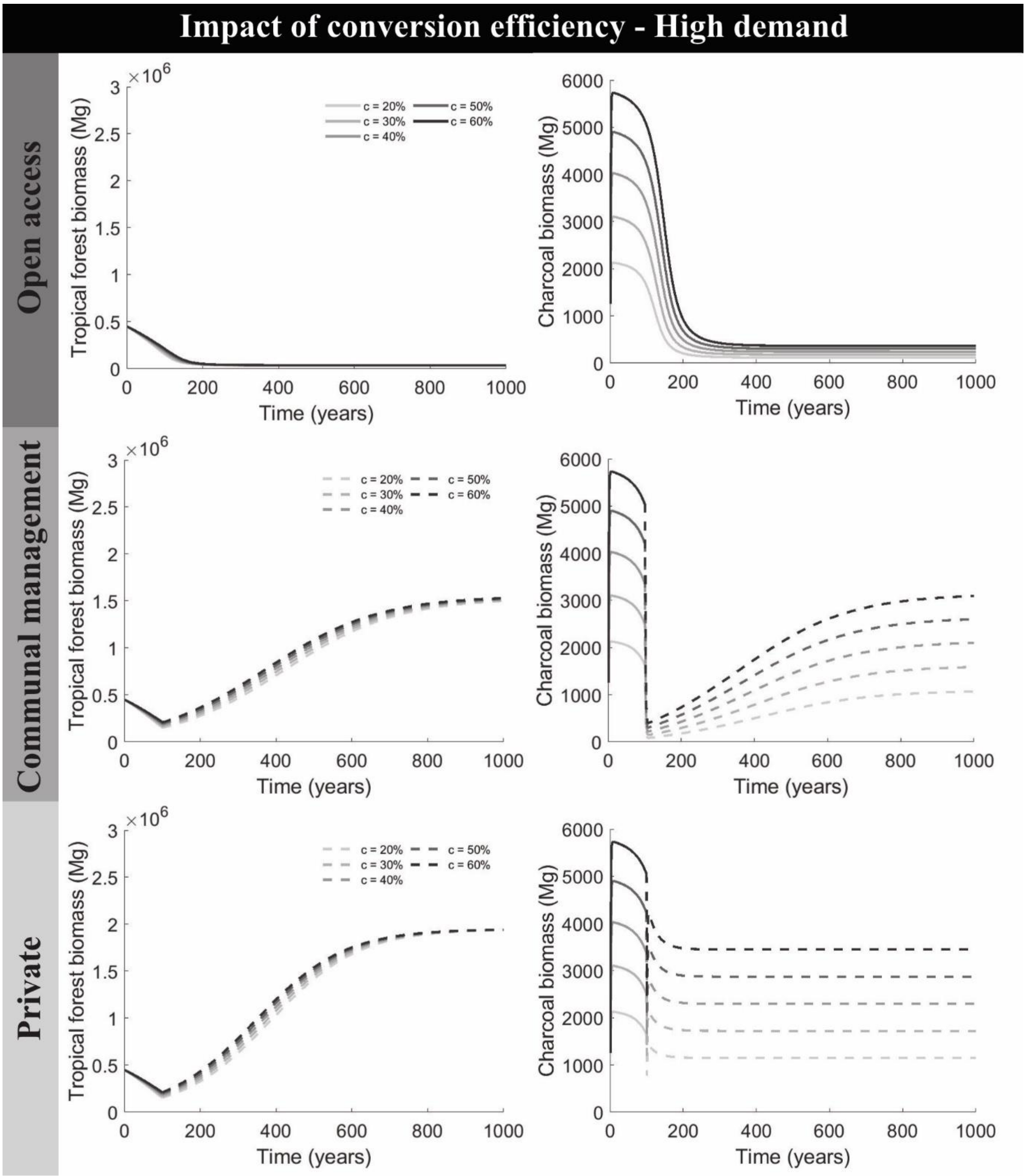


**Figure B3.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels carbonization efficiency (*c*). Every line indicates a certain rate of carbonization efficiency (see legends). The carbonization efficiency is indicated by different gray tones, from light grain for low carbonization efficiencies to black for high carbonization efficiencies. A transition from an initially open access system after 100 years is simulated for every forest growth rate. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (Supplementary Materials A). **Demand levels are set at 60,000 Mg.**

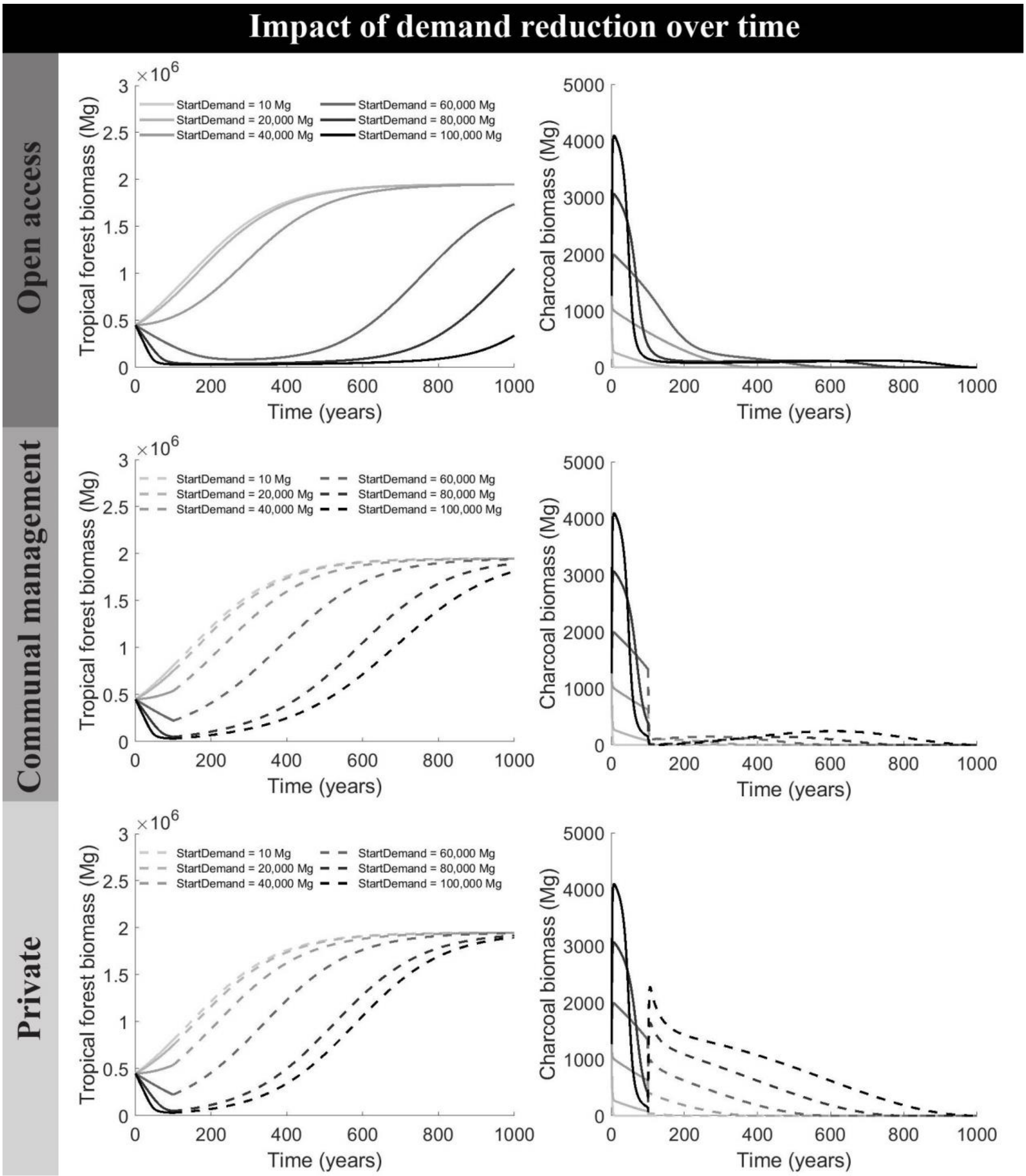


**Figure B4.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production simulated along a gradient of declining demand. The level of demand starts at 10 to 100,000 Mg.year$^{-1}$ (see legends; StartDemand) and demand subsequently declines with 100 Mg.year$^{-1}$ to simulate an intervention that reduces demand over time. Every line indicates a certain level of demand. A transition from an initially open access system after 100 years is simulated for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

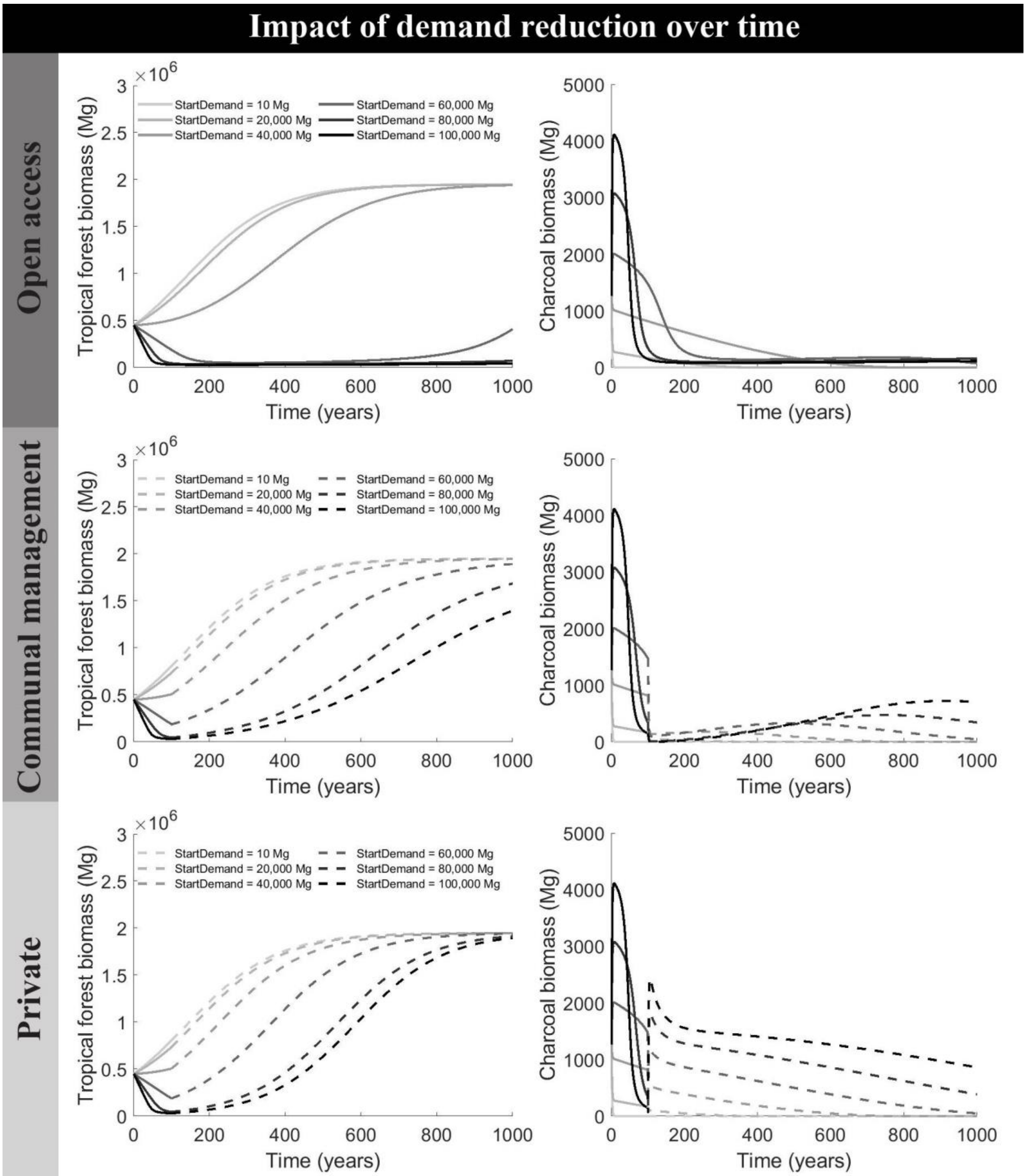


**Figure B5.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production simulated along a gradient of declining demand. The level of demand starts at 10 to 100,000 Mg.year$^{-1}$ (see legends; StartDemand) and demand subsequently declines with 50 Mg.year$^{-1}$ to simulate an intervention that reduces demand over time. Every line indicates a certain level of demand. A transition from an initially open access system after 100 years is simulated for every level of demand. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (see Supplementary Materials A of this article).

## Supplementary materials C

This Supplementary Materials provides a sensitivity analysis of the model. We examined the effects of changes in (i) point at which half of the maximal charcoal capacity is reached, (ii) forest carrying capacity, (iii) harvesting intensities and (iv) forest growth rates. We simulated the effect of these parameters within the realistic ranges depicted in Table A1. Overall, none of these parameters has a predominantly large impact on the model simulations or completely changes the dynamics of the model. Population growth rate ($n$) has minimal impact within the ranges depicted in Table A1 hence we did not provide a figure for this parameter here. Besides this, the point at which half of the maximal charcoal capacity is reached ($v$), only affects the dynamics of open access systems. Hence, we only provided a figure for open access systems for this parameter.

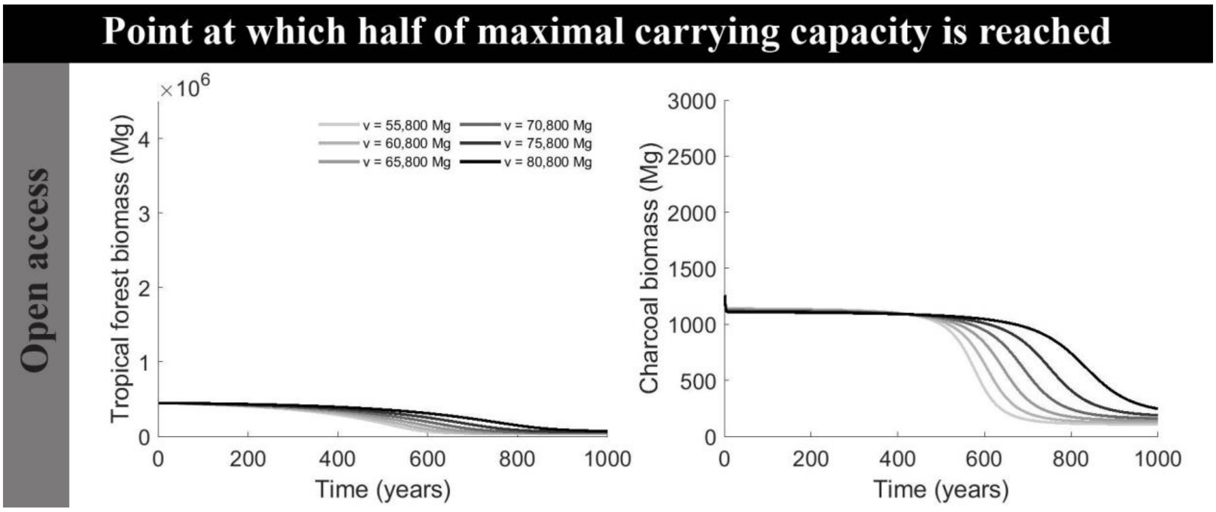


**Figure C1.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production at different points at which half of the maximal charcoal capacity is reached ($v$). Every line indicates a certain point at which half of the maximal charcoal capacity is reached (see legends). The point at which half of the maximal charcoal capacity is reached is indicated by different gray tones, from light grain for low points at which half of the maximal charcoal capacity is reached to black for high points at which half of the maximal charcoal capacity is reached. We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (Supplementary Materials A). **Demand levels are set at 42,000 Mg.**

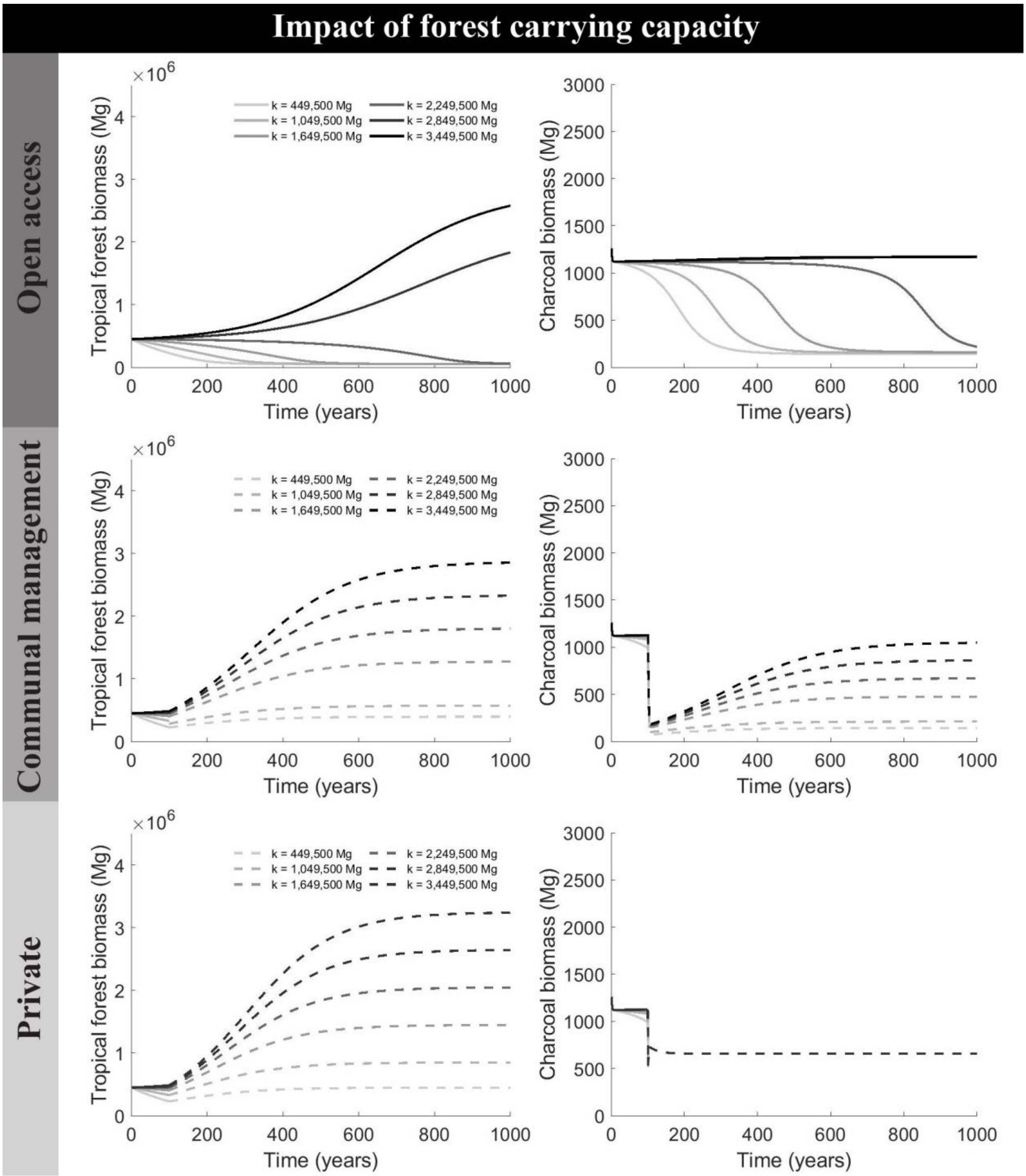


**Figure C2.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of forest carrying capacity (*K*). Every line indicates a certain forest carrying capacity (see legends). The forest carrying capacity is indicated by different gray tones, from light grain for low carrying capacities to black for high carrying capacities. A transition from an initially open access system after 100 years is simulated for every forest carrying capacity. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (Supplementary Materials A). **Demand levels are set at 42,000 Mg.**

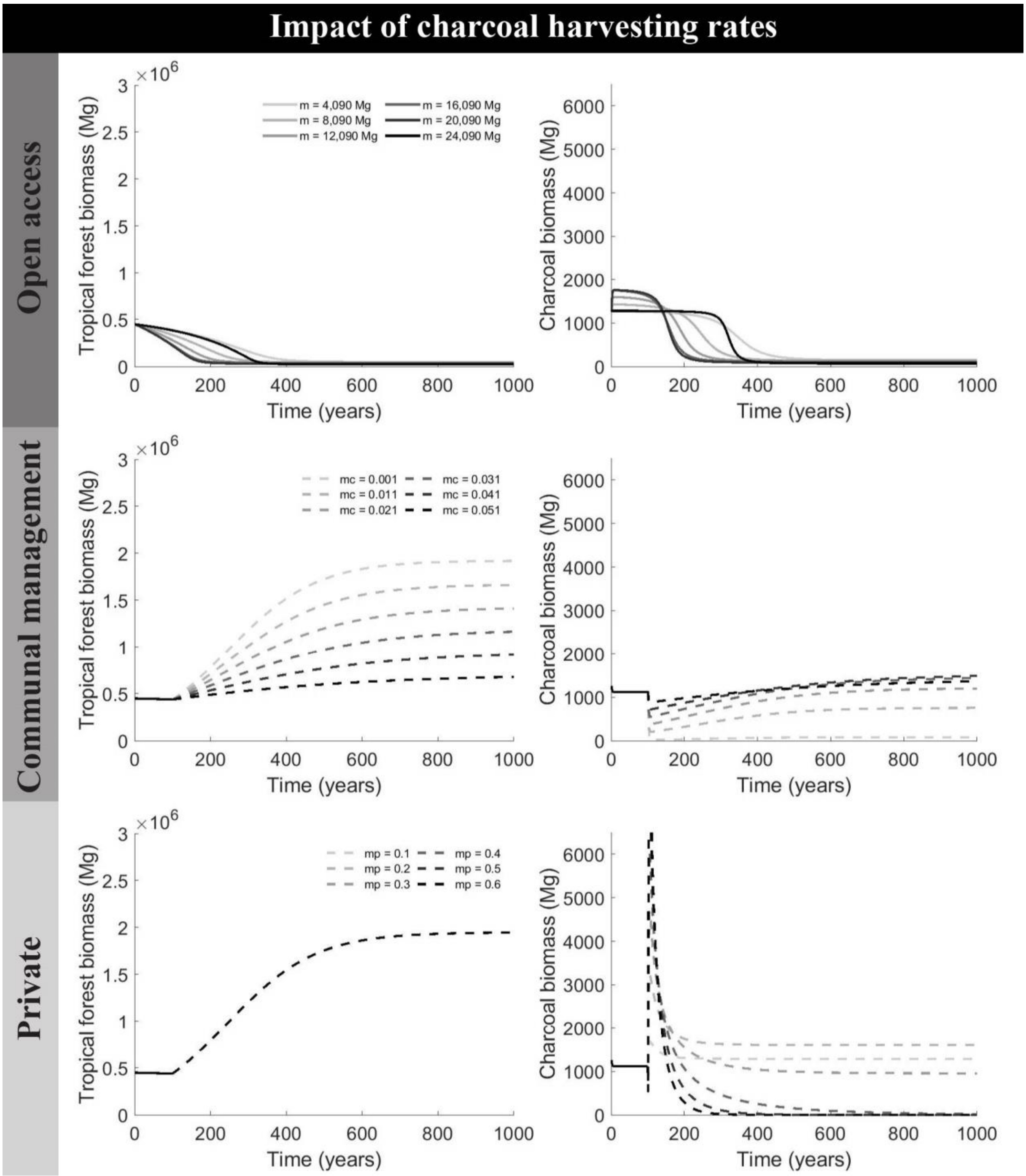


**Figure C3.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different harvesting intensities (*m*, $m_c$, $m_p$). Every line indicates a certain harvesting intensity (see legends). The harvesting intensity level is indicated by different gray tones, from light grain for low harvesting intensities to black for high harvesting intensities. A transition from an initially open access system after 100 years is simulated for every harvesting intensity. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (Supplementary Materials A). **Demand levels are set at 42,000 Mg.**

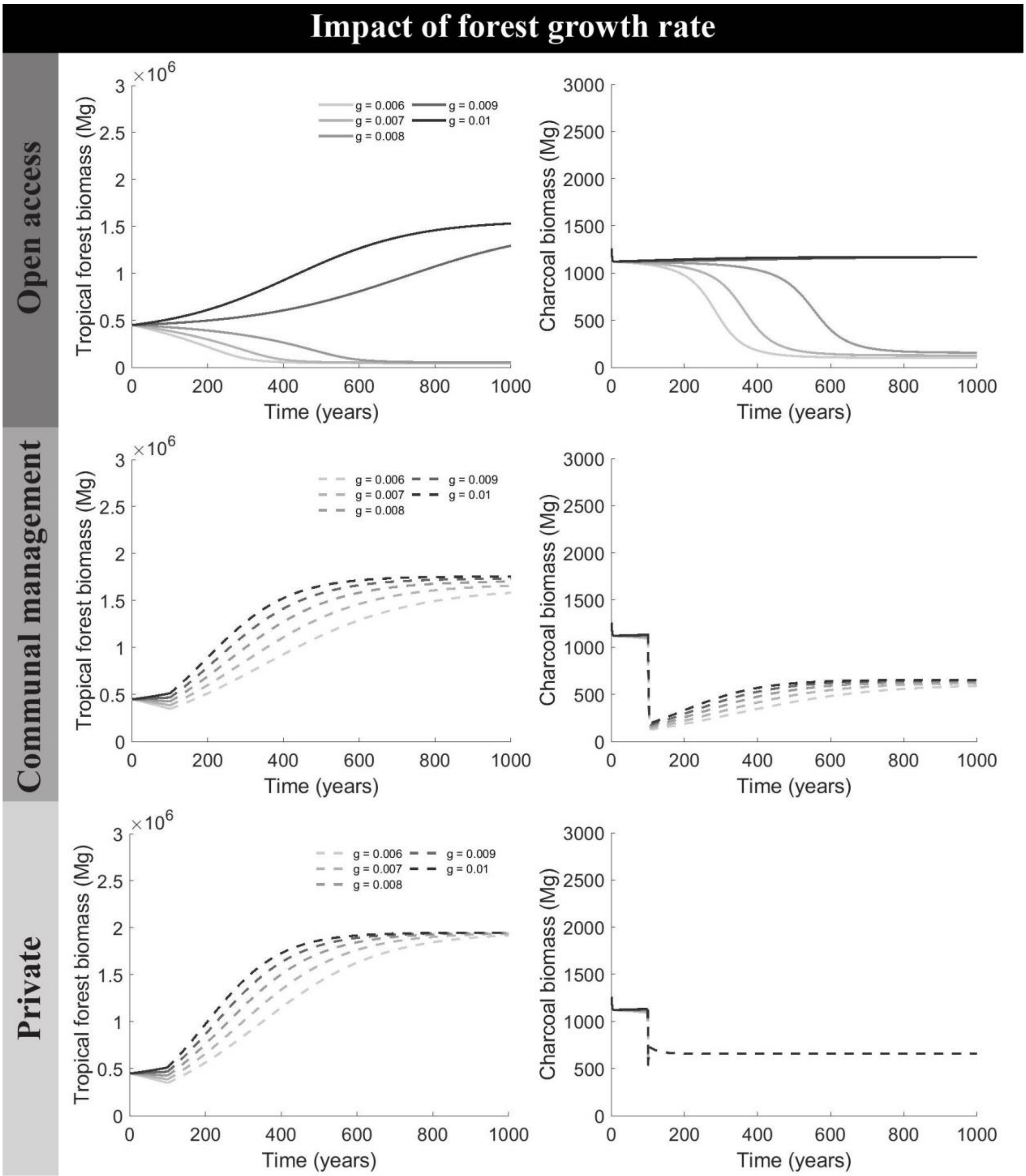


**Figure C4.** Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of forest growth rates (*g*). Every line indicates a certain rate of forest growth (see legends). The forest growth rate is indicated by different gray tones, from light grain for low forest growth rates to black for high forest growth rates. A transition from an initially open access system after 100 years is simulated for every forest growth rate. The transition is visualized by a change in line style from solid (open access dynamics) to dashed (communal management or private). We start all our simulations at a tropical forest biomass level of 449,500 Mg and a charcoal biomass level of 1,260 Mg (Supplementary Materials A). **Demand levels are set at 42,000 Mg.**

# Appendix Chapter 4

## Appendix A:

**Table A1.** Image acquisition and processing dates for the 19 Landsat-9 images included in this study. The tile is LC08_L1TP.

| Image | Acquisition date | Processing date |
|---|---|---|
| 1 | 2019.01.25 | 2019.02.05 |
| 2 | 2019.02.10 | 2019.02.22 |
| 3 | 2019.02.26 | 2019.03.09 |
| 4 | 2019.03.14 | 2019.03.25 |
| 5 | 2019.04.15 | 2019.04.23 |
| 6 | 2019.05.17 | 2019.05.21 |
| 7 | 2019.06.02 | 2019.06.05 |
| 8 | 2019.06.18 | 2019.07.03 |
| 9 | 2019.07.04 | 2019.07.18 |
| 10 | 2019.07.20 | 2019.07.31 |
| 11 | 2019.08.05 | 2019.08.20 |
| 12 | 2019.08.21 | 2019.09.03 |
| 13 | 2019.09.06 | 2019.09.17 |
| 14 | 2019.09.22 | 2019.09.26 |
| 15 | 2019.10.08 | 2019.10.18 |
| 16 | 2019.10.24 | 2019.10.30 |
| 17 | 2019.11.25 | 2019.12.03 |
| 18 | 2019.12.11 | 2019.12.17 |
| 19 | 2019.12.27 | 2020.01.10 |

**Table A2.** Average Importance for all input bands and indices for the Landsat-8 method. Mean = The mean calculated across all satellite imagery for the year 2019 per band and index. The Mean Decrease Gini measures how each band and index contributes to the homogeneity of the nodes and leaves of the Random Forest. Mean Decrease Accuracy measures how the prediction error of the out of bag (OOB) data of the random forest differs on average from the prediction error of the OOB after predictor variables are permuted, normalized for the standard deviation. The higher the average Importance values, the more important this band / index is. CoV= The coefficient of variation calculated across all satellite imagery for the year 2019 per band and index. NDVI = Normalized Difference Vegetation Index, NDWI = Normalized Difference Water Index, BSI = Bare Soil Index, NBR = Normalized Burn Ratio. The four highest values per Importance measure are marked in red.

| **Bands** | **Mean Decrease Accuracy (MDA)** | **Mean Decrease Gini** | **MDA Charcoal** | **MDA Forest** | **MDA Non-forest** |
|---|---|---|---|---|---|
| Band 01 (mean) | 25.75 | 11.16 | 27.94 | 12.09 | 3.39 |
| Band 02 (mean) | 24.61 | 19.35 | 20.40 | 16.48 | 13.73 |
| Band 03 (mean) | 53.58 | 42.92 | 38.72 | 24.43 | 50.65 |
| Band 04 (mean) | 25.64 | 19.19 | 22.24 | 16.09 | 13.44 |
| Band 05 (mean) | 18.20 | 7.09 | 16.17 | 5.28 | 8.98 |
| Band 06 (mean) | 21.45 | 12.96 | 22.94 | 13.13 | 4.74 |
| Band 07 (mean) | 27.70 | 16.56 | 12.80 | 22.02 | 17.93 |
| NBR (mean) | 16.79 | 10.41 | 14.00 | 12.15 | 6.44 |
| NDVI (mean) | 22.17 | 15.57 | 16.85 | 12.41 | 16.48 |
| NDWI (mean) | 16.62 | 10.44 | 14.09 | 11.95 | 6.66 |
| BSI (mean) | 17.33 | 10.39 | 12.79 | 11.43 | 10.48 |
| Band 01 (CoV) | 16.16 | 6.64 | 15.72 | 8.00 | 0.40 |
| Band 02 (CoV) | 14.52 | 5.78 | 10.16 | 9.39 | 5.38 |
| Band 03 (CoV) | 14.99 | 6.46 | 13.01 | 6.72 | 5.11 |
| Band 04 (CoV) | 23.56 | 10.42 | 17.75 | 13.63 | 13.90 |
| Band 05 (CoV) | 15.04 | 6.40 | 11.12 | 7.82 | 7.39 |
| Band 06 (CoV) | 24.54 | 10.53 | 16.87 | 14.84 | 15.33 |
| Band 07 (CoV) | 20.56 | 8.51 | 14.98 | 11.11 | 8.89 |
| NBR (CoV) | 14.35 | 6.88 | 17.08 | 6.43 | -5.11 |
| NDVI (CoV) | 16.17 | 7.63 | 10.01 | 11.53 | 5.29 |
| NDWI (CoV) | 14.44 | 6.89 | 17.32 | 6.46 | -5.15 |
| BSI (CoV) | 9.30 | 5.15 | 9.08 | 5.38 | -0.74 |

**Table A3.** Average importance of all input bands and indices for the Sentinel-2 method. The Mean Decrease Gini measures how each band and index contributes to the homogeneity of the nodes and leaves of the Random Forest. Mean Decrease Accuracy measures how the prediction error of the out of bag (OOB) data of the random forest differs on average from the prediction error of the OOB after predictor variables are permuted, normalized for the standard deviation. The higher the average Importance values, the more important this band / index is. NDVI = Normalized Difference Vegetation Index, NDWI = Normalized Difference Water Index, BSI = Bare Soil Index, NBR = Normalized Burn Ratio. The four highest values per Important measure have been marked in red.

| **Bands and indices** | **Mean Decrease Accuracy (MDA)** | **Mean Decrease Gini** | **MDA Charcoal** | **MDA Forest** | **MDA Non-forest** |
|---|---|---|---|---|---|
| B02 | 37.00 | 25.77 | 28.32 | 19.55 | 26.40 |
| B03 | 46.68 | 29.17 | 37.12 | 14.78 | 38.51 |
| B04 | 27.63 | 18.61 | 16.28 | 19.84 | 15.12 |
| B05 | 22.69 | 11.10 | 18.57 | 12.13 | 10.10 |
| B06 | 29.18 | 12.29 | 21.05 | 9.83 | 19.08 |
| B07 | 23.38 | 9.80 | 17.1 | 8.01 | 13.18 |
| B8A | 26.17 | 10.60 | 20.67 | 12.17 | 12.03 |
| B11 | 37.03 | 20.40 | 34.48 | 20.86 | 13.76 |
| B12 | 33.35 | 19.89 | 19.03 | 27.5 | 15.12 |
| BSI | 29.68 | 17.05 | 27.72 | 13.45 | 13.74 |
| NBR | 34.11 | 25.88 | 21.32 | 22.34 | 21.85 |
| NDVI | 28.65 | 20.83 | 20.63 | 17.71 | 17.89 |
| NDWI | 34.10 | 25.80 | 21.62 | 22.55 | 21.65 |

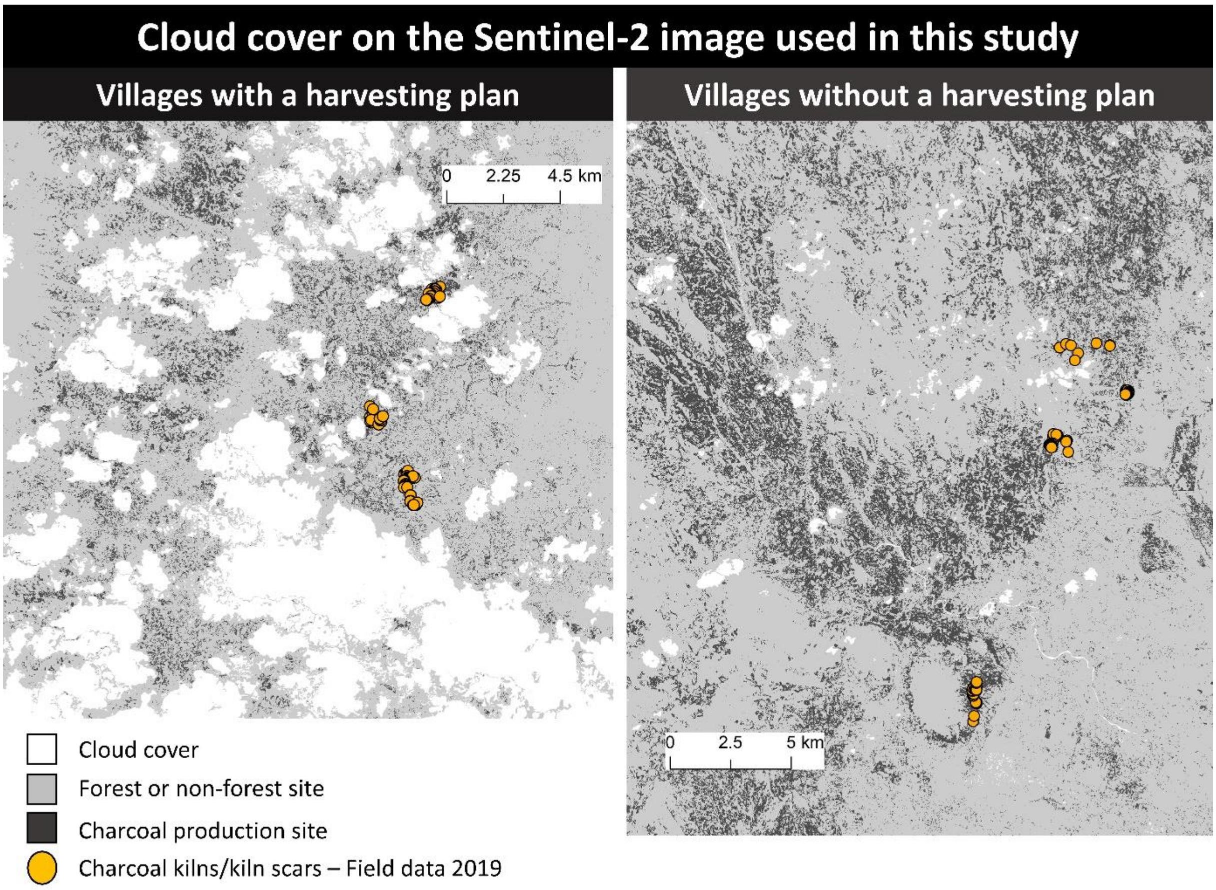


**Figure A1.** Cloud cover in the Sentinel-2 image covering our study area with acquisition data 12th of August 2019. It can be observed that the amount of cloud cover is higher in villages with a harvesting plan than in villages without a harvesting plan.

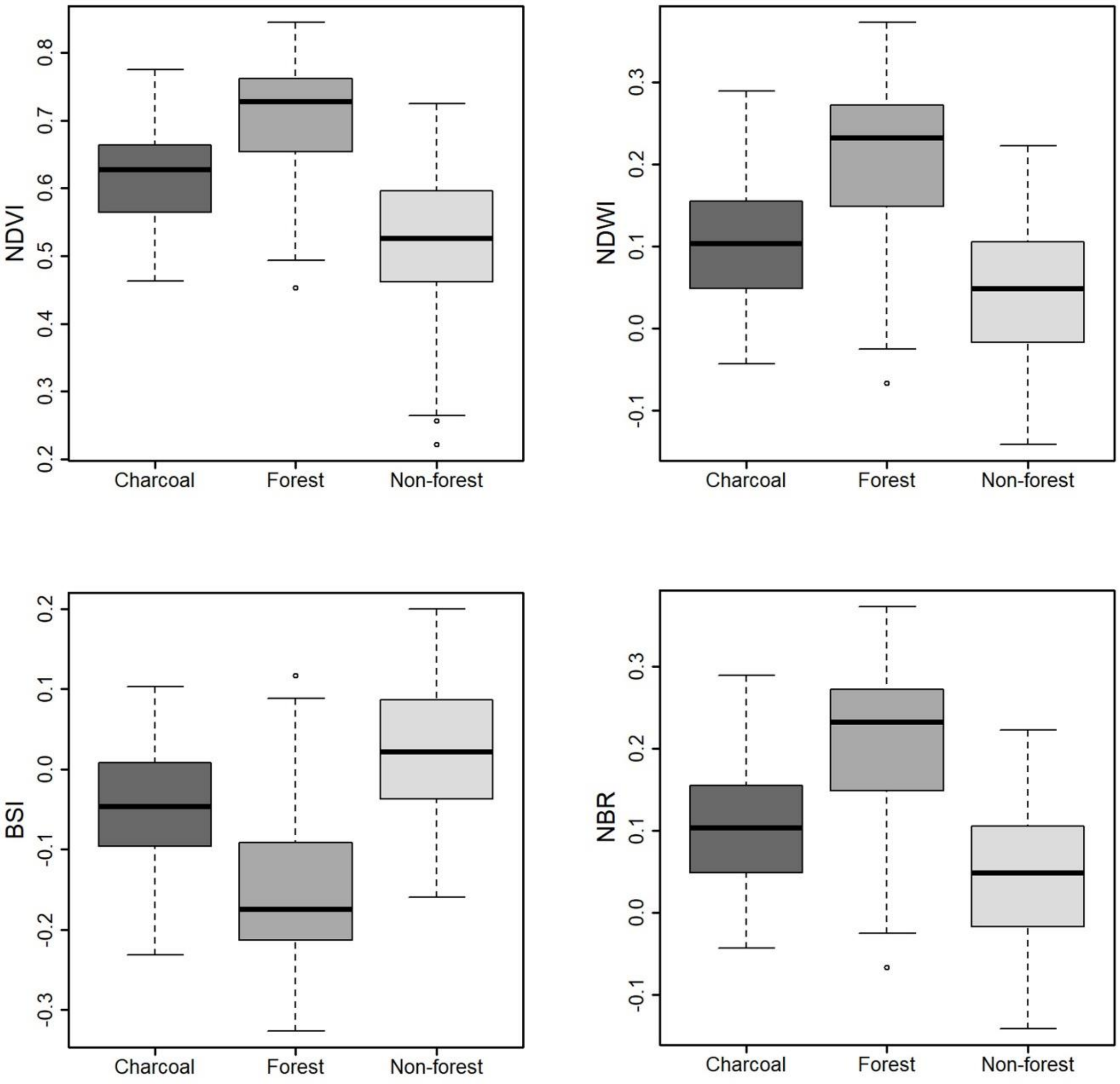


**Figure A2.** The mean of NDVI, NDWI, BSI, and NBR calculated over 19 Landsat-8 images of the year 2019. The boxplots include data for the 184 locations per class. We find differences in index values between (i) charcoal sites, (ii) forest sites, and (iii) non-forest sites. NDVI = Normalized Difference Vegetation Index, NDWI = Normalized Difference Water Index, BSI = Bare Soil Index and NBR = Normalized Burn Ratio

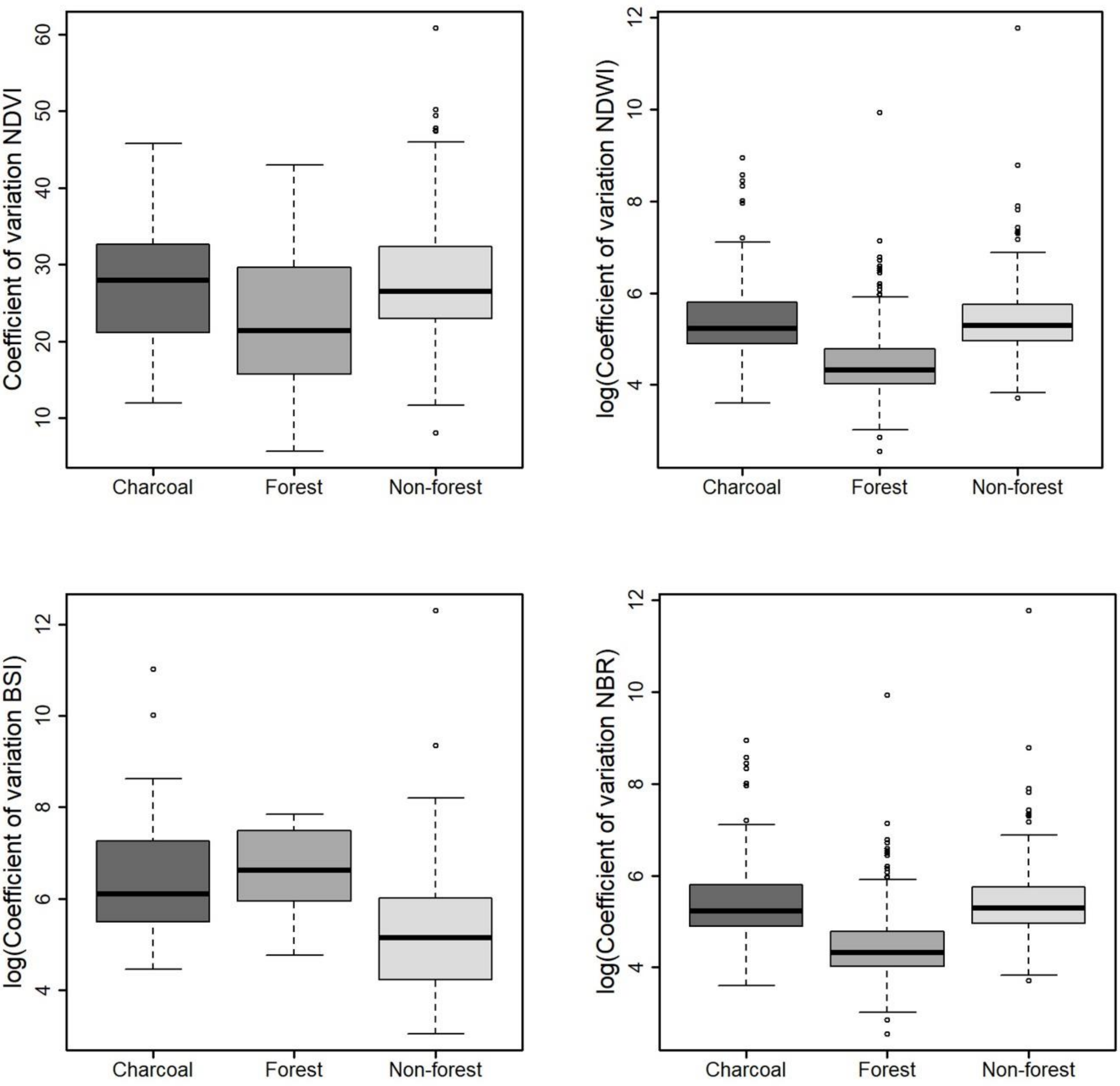


**Figure A3.** The coefficient of variation of NDVI, NDWI, BSI and NBR calculated over 19 Landsat-8 images of the year 2019. The boxplots data for the184 locations per class. We find differences can be seen in index values between (i) charcoal sites, (ii) forest sites, and (iii) non-forest sites. NDVI = Normalized Difference Vegetation Index, NDWI = Normalized Difference Water Index, BSI = Bare Soil Index and NBR = Normalized Burn Ratio.

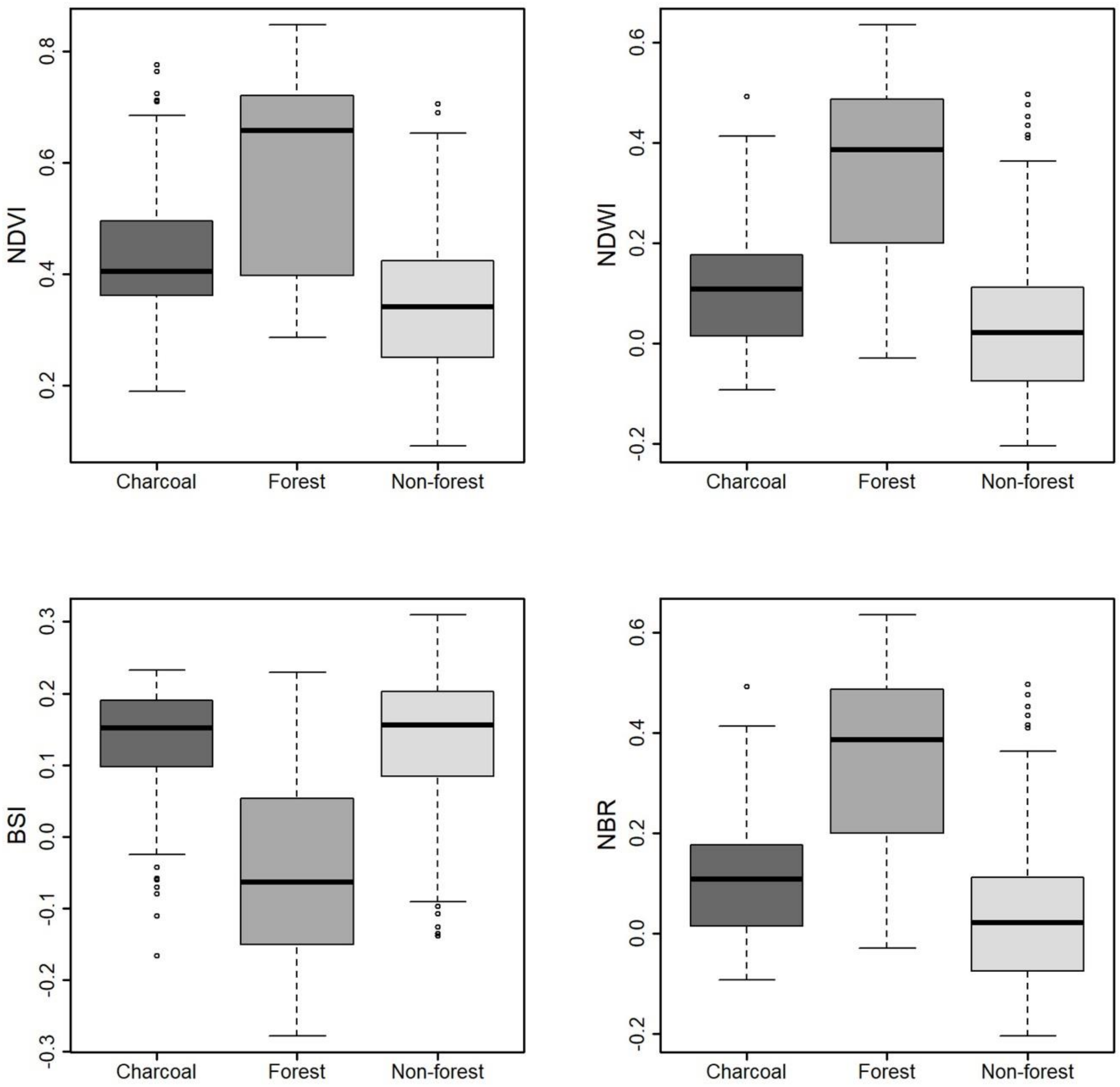


**Figure A4.** NDVI, NDWI, BSI and NBR calculated over one Sentinel-2 image of the year 2019 used in this study. The boxplots include data for the 184 locations per class. We observed differences in index value between (i) charcoal sites, (ii) forest sites, and (iii) non-forest sites. NDVI = Normalized Difference Vegetation Index, NDWI = Normalized Difference Water Index, BSI = Bare Soil Index and NBR = Normalized Burn Ratio.

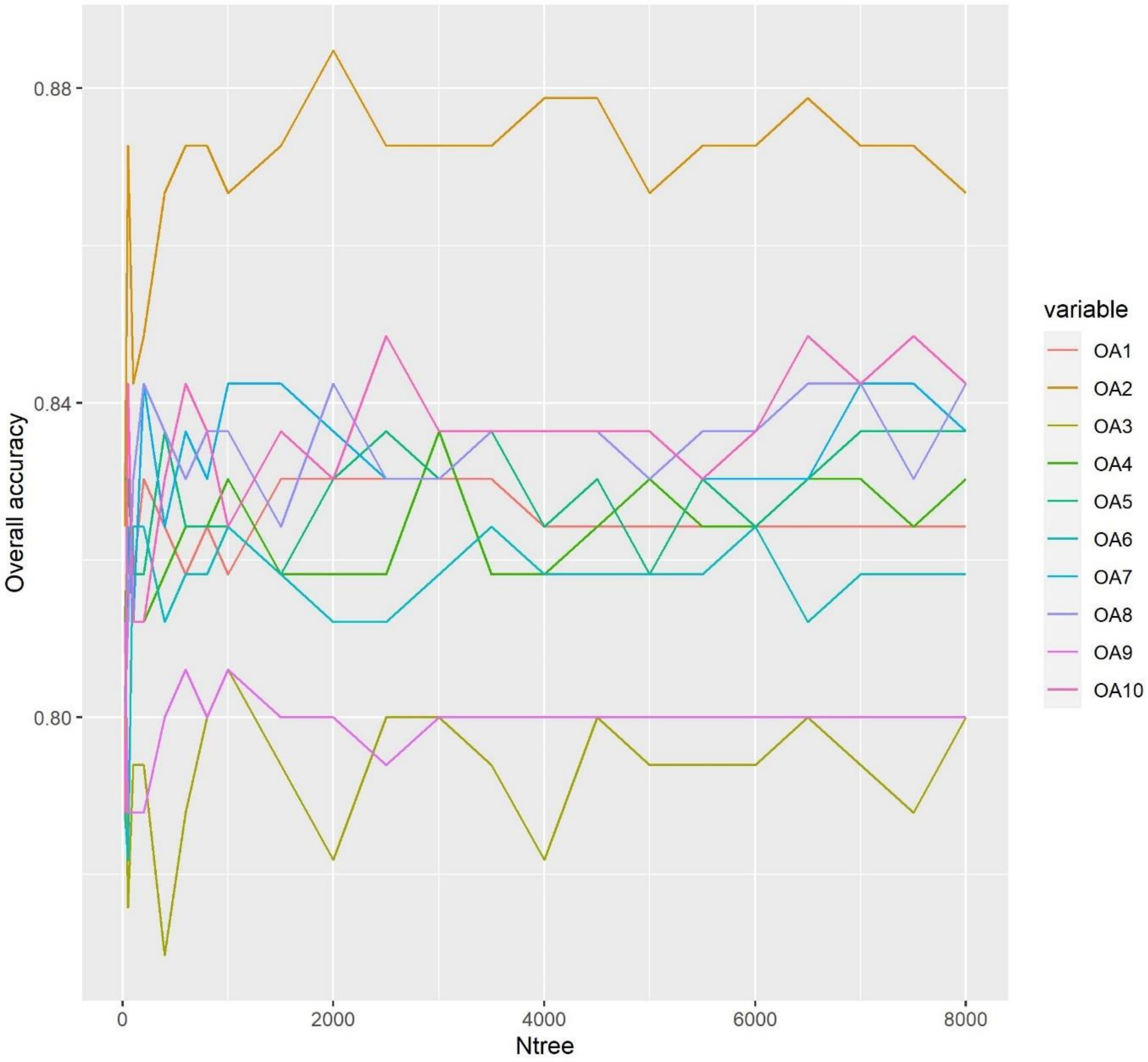


**Figure A5.** Sensitivity of the RF Landsat-8 classifier to the random selection of test and training data and the Ntree (number of trees) variable. We randomly selected 10 test and training datasets and computed the overall accuracy for each of these for Ntrees ranging between 0 and 8000. Results indicate that the RF Landsat-8 classifier is sensitive to test and training data selection with a deviation in overall accuracy of about 10% maximum, but mostly ranging between 82% and 84%.

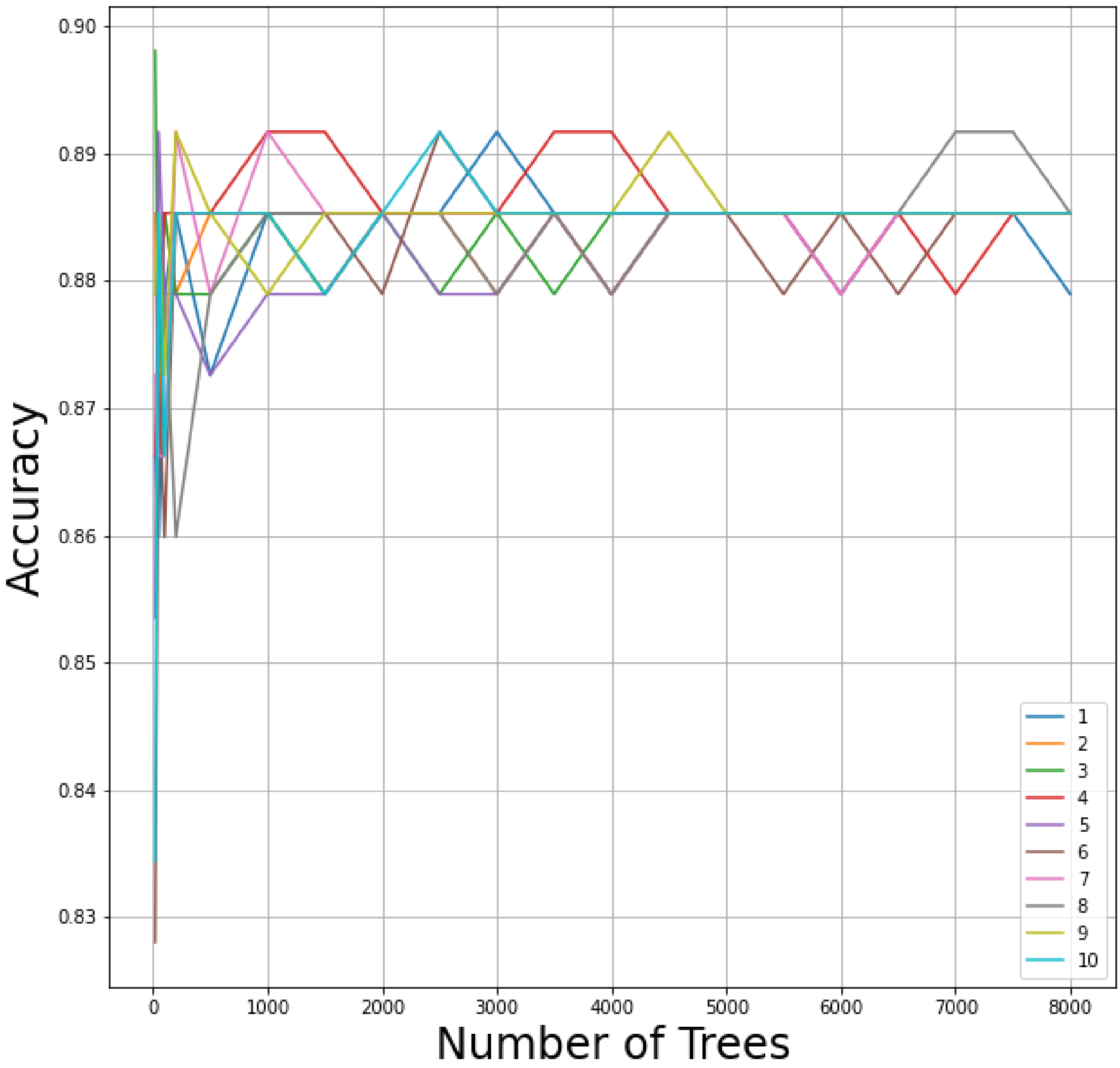


**Figure A6.** Sensitivity of the RF Sentinel-2 classifier to the random selection of test and training data and the number of trees (Ntree) variable. We randomly selected 10 test and training datasets and computed the overall accuracy for each of these for Ntrees ranging between 0 and 8000. Results indicate that the RF Sentinel-2 classifier is relatively unsensitive to test and training data selection with a deviation in overall accuracy mostly ranging between 0.88 and 0.89. We observe stabilization at Ntree = 1000.

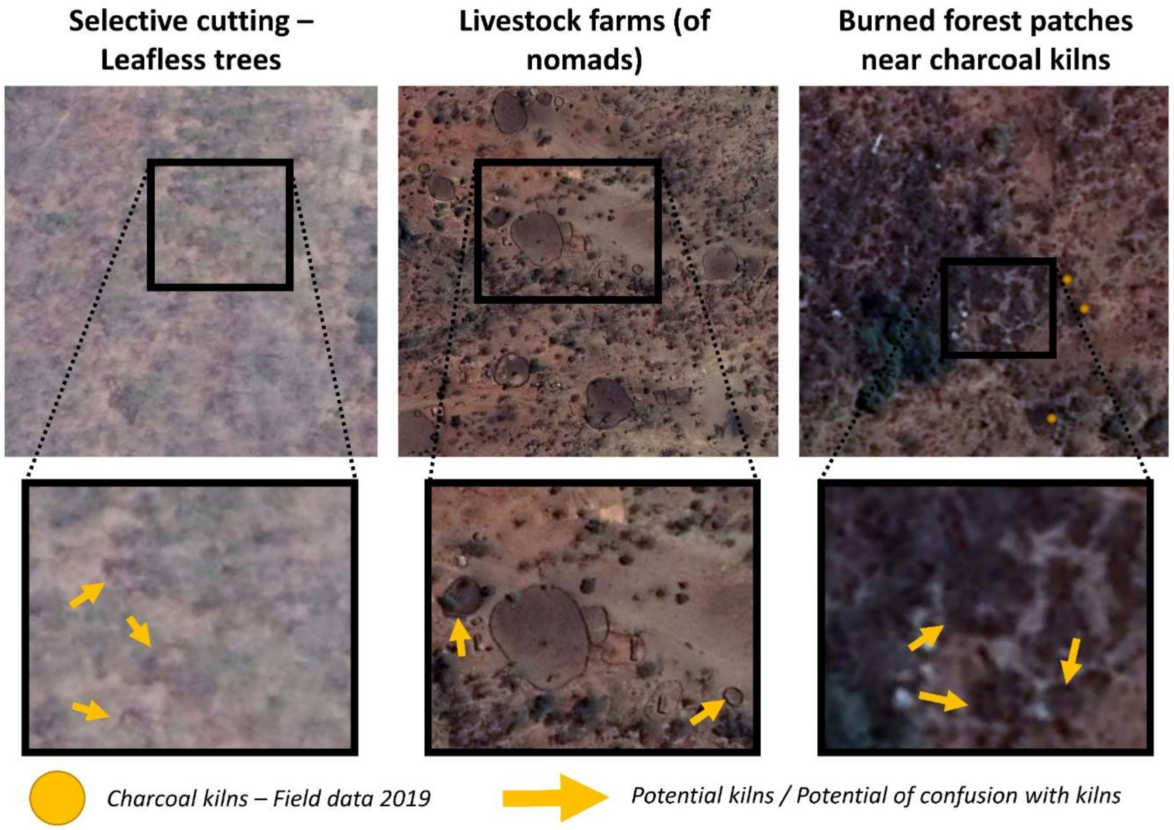


**Figure A7.** Examples of features observed in the landscape on Worldview-2 for one village without harvesting plan in the year 2019. These features include leafless trees, livestock farms and burnt forest patches near kiln sites.

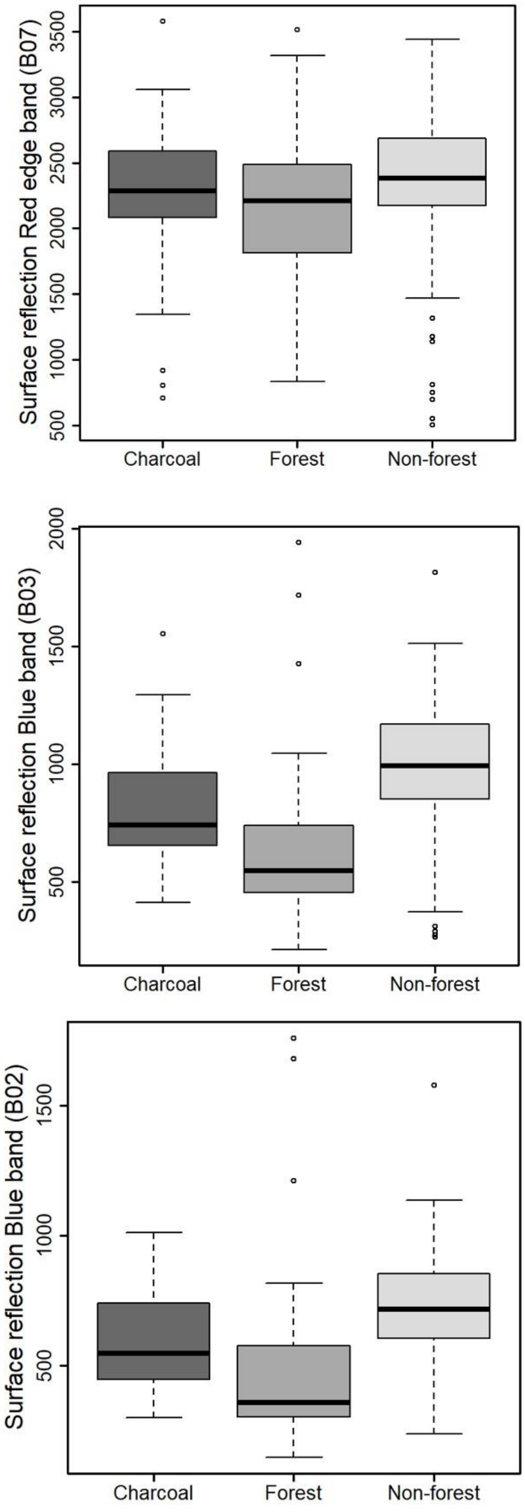


**Figure A8.** Surface reflectance of Band7 (Red-edge), Band 3 (Green) and Band 2 (Blue) for Sentinel-2. The boxplots include data for the 184 locations per class. On average, we find differences in surface reflectance between (i) charcoal, (ii) forest, and (iii) non-forest sites. Sentinel-2 level-2A surface reflectance data was multiplied by 10,000 for purposes of display (Main-Knorn *et al* 2017).

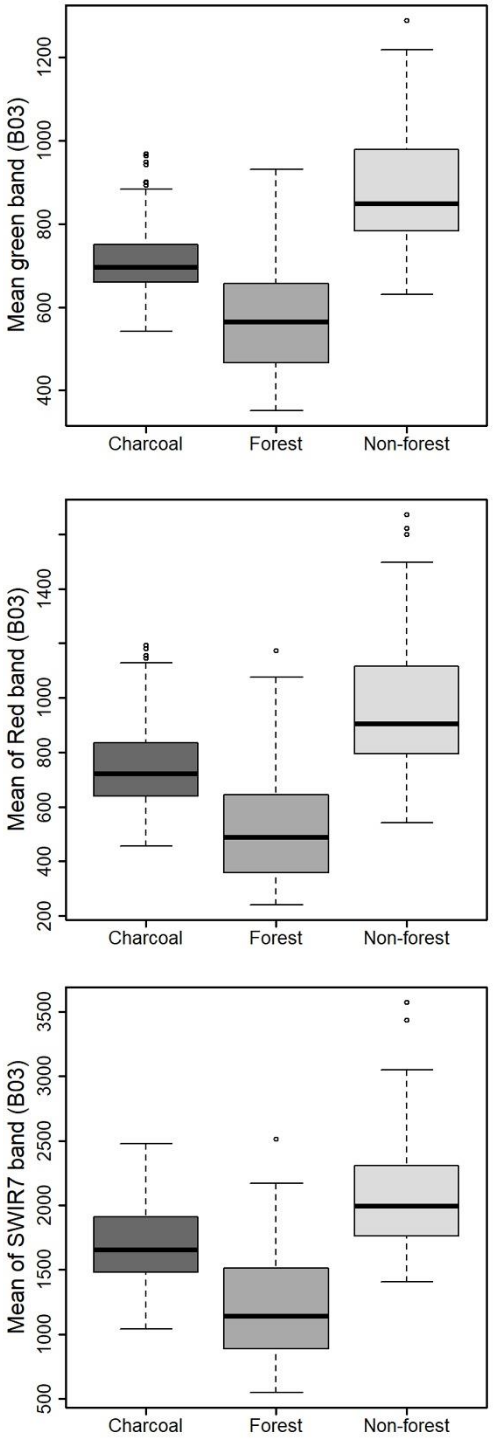


**Figure A9.** The mean of surface reflectance for the Landsat-8 images analyzed in this study. On average, we find differences in surface reflectance between (i) charcoal, (ii) forest, and (iii) non-forest sites. All downloaded Landsat-8 surface reflectance data was multiplied by 10,000 for calculation and display purposes (USGS 2020).

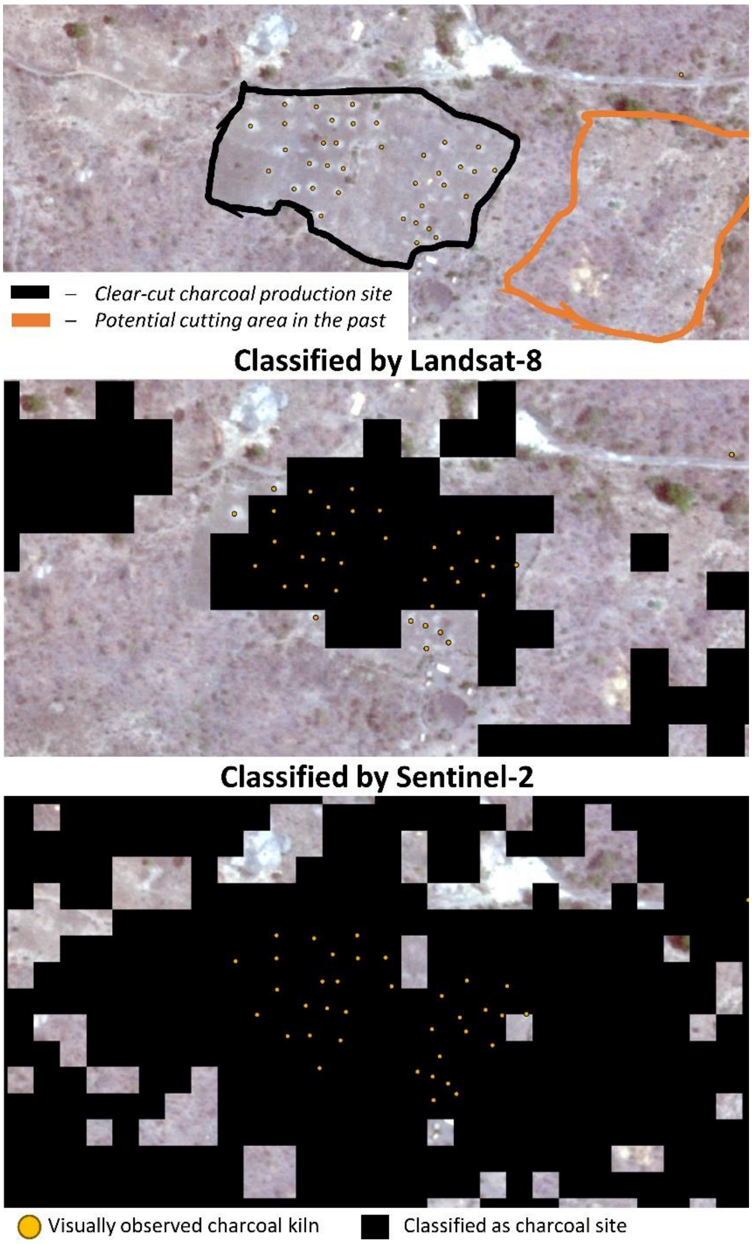


**Figure A10.** An example of over-prediction of charcoal production sites through Landsat-8 and Sentinel-2 classification. We observe more severe over-prediction by Sentinel-2 classification, despite the higher overall accuracy and kappa coefficient compared to Landsat-8 classification.

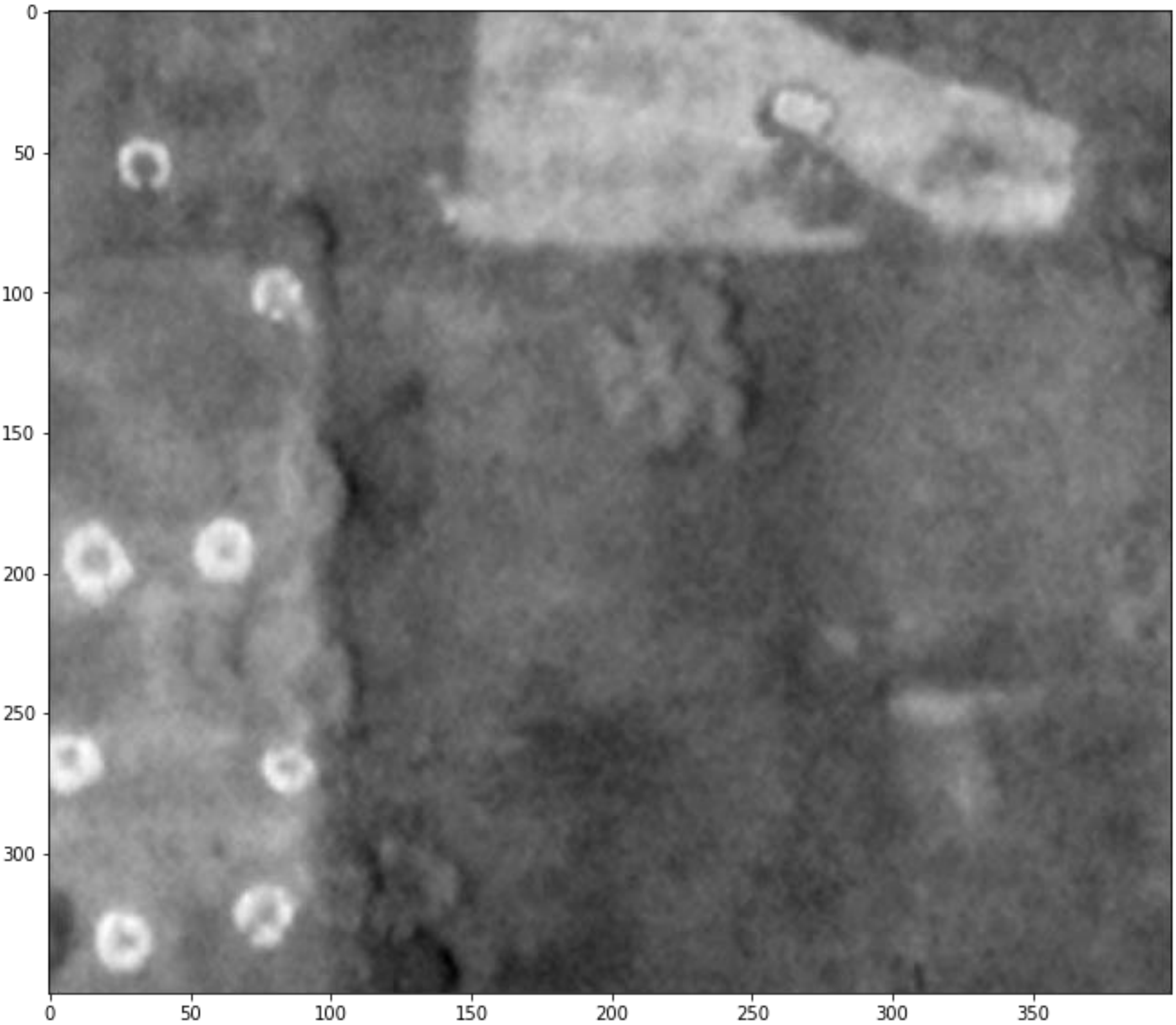
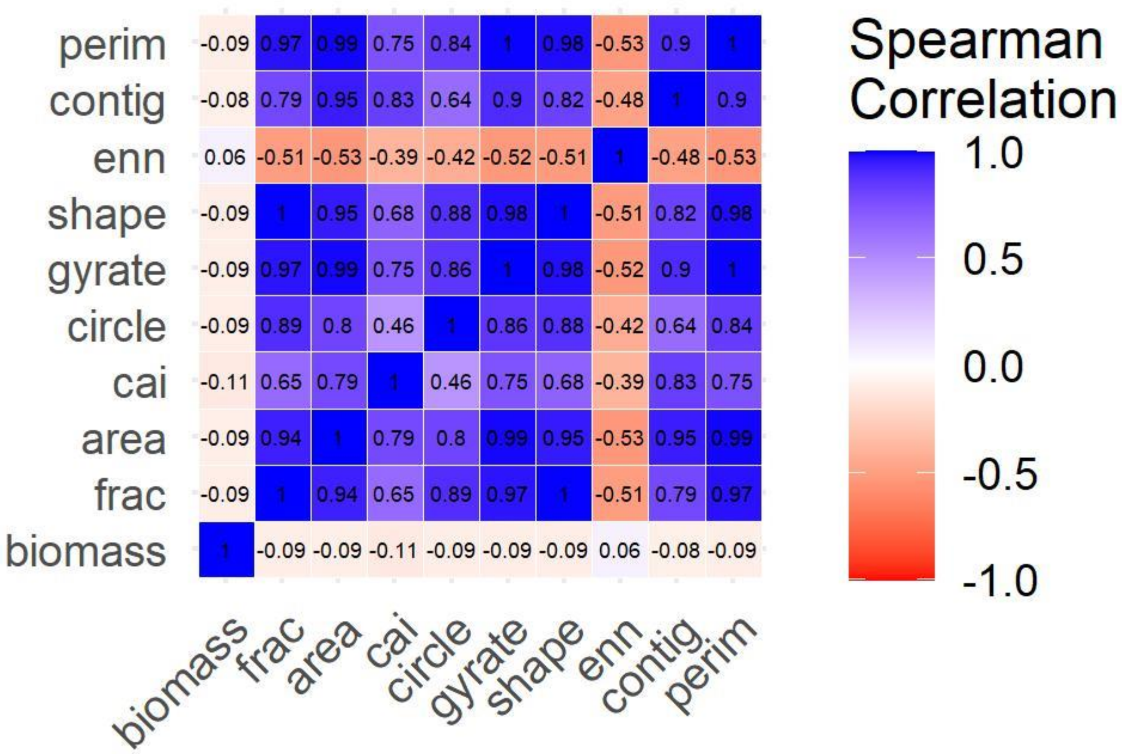


**Figure A11.** Sugarcane piles detected through contrast metric in the study area on a Planet image. The shapes were identified as sugarcane piles by an expert from the Universidad Nacional Autónoma de México (UNAM). Although the shapes are slightly larger and more rounded, it is likely that we have confused sugarcane piles with charcoal kilns in agricultural areas, which may explain mismatches in these areas.

# Appendix Chapter 5

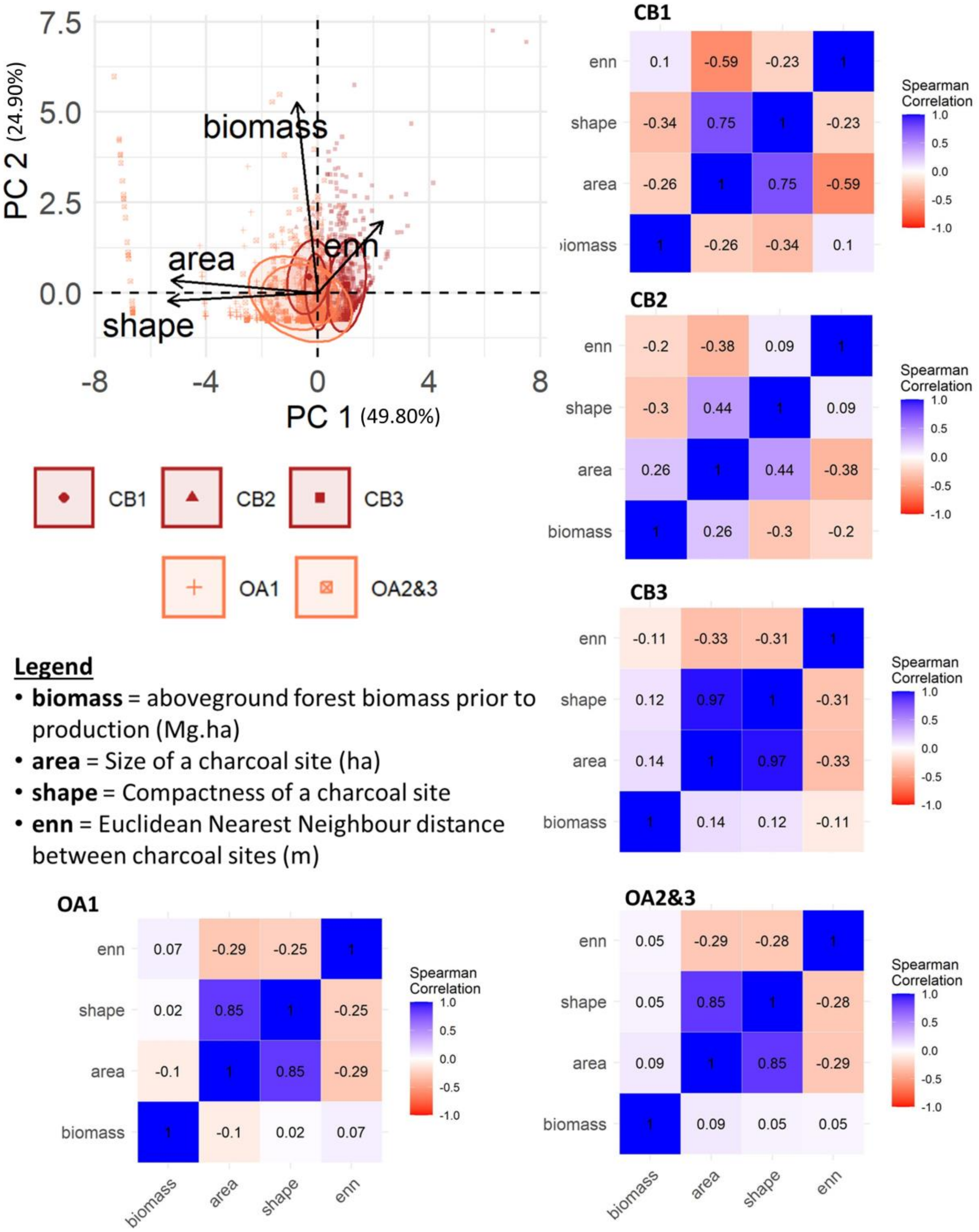
## Appendix A

*Figures:*



| | biomass | frac | area | cai | circle | gyrate | shape | enn | contig | perim |
|---|---|---|---|---|---|---|---|---|---|---|
| perim | -0.09 | 0.97 | 0.99 | 0.75 | 0.84 | 1 | 0.98 | -0.53 | 0.9 | 1 |
| contig | -0.08 | 0.79 | 0.95 | 0.83 | 0.64 | 0.9 | 0.82 | -0.48 | 1 | 0.9 |
| enn | 0.06 | -0.51 | -0.53 | -0.39 | -0.42 | -0.52 | -0.51 | 1 | -0.48 | -0.53 |
| shape | -0.09 | 1 | 0.95 | 0.68 | 0.88 | 0.98 | 1 | -0.51 | 0.82 | 0.98 |
| gyrate | -0.09 | 0.97 | 0.99 | 0.75 | 0.86 | 1 | 0.98 | -0.52 | 0.9 | 1 |
| circle | -0.09 | 0.89 | 0.8 | 0.46 | 1 | 0.86 | 0.88 | -0.42 | 0.64 | 0.84 |
| cai | -0.11 | 0.65 | 0.79 | 1 | 0.46 | 0.75 | 0.68 | -0.39 | 0.83 | 0.75 |
| area | -0.09 | 0.94 | 1 | 0.79 | 0.8 | 0.99 | 0.95 | -0.53 | 0.95 | 0.99 |
| frac | -0.09 | 1 | 0.94 | 0.65 | 0.89 | 0.97 | 1 | -0.51 | 0.79 | 0.97 |
| biomass | 1 | -0.09 | -0.09 | -0.11 | -0.09 | -0.09 | -0.09 | 0.06 | -0.08 | -0.09 |

**Figure A1.** Spearman correlation matrix showing the correlations between patch metrics of the "landscapemetrics" packages of R (Hesselbarth et al 2021). Perimeter = Perimeter-area ratio, Contig = Contiguity index, enn = Euclidean nearest-neighbor distance, shape = Patch shape, gyrate = Radius of Gyration, circle = Related circumscribing circle, cai = Core area index, area = Patch area, frac = Fractal dimension index, biomass = Aboveground biomass prior to charcoal production (see Hesselbarth et al. (2021) for a description of all patch metrics). Because of high correlations between patch metrics, we selected three metrics that best fit the charcoal site pattern attributes we assess in this paper, namely the size, shape and density of charcoal sites.



**Legend**
- **biomass** = aboveground forest biomass prior to production (Mg.ha)
- **area** = Size of a charcoal site (ha)
- **shape** = Compactness of a charcoal site
- **enn** = Euclidean Nearest Neighbour distance between charcoal sites (m)

**CB1**

| | | | | |
|---|---|---|---|---|
| enn | 0.1 | -0.59 | -0.23 | 1 |
| shape | -0.34 | 0.75 | 1 | -0.23 |
| area | -0.26 | 1 | 0.75 | -0.59 |
| iomass | 1 | -0.26 | -0.34 | 0.1 |

**CB2**

| | | | | |
|---|---|---|---|---|
| enn | -0.2 | -0.38 | 0.09 | 1 |
| shape | -0.3 | 0.44 | 1 | 0.09 |
| area | 0.26 | 1 | 0.44 | -0.38 |
| biomass | 1 | 0.26 | -0.3 | -0.2 |

**CB3**

| | | | | |
|---|---|---|---|---|
| enn | -0.11 | -0.33 | -0.31 | 1 |
| shape | 0.12 | 0.97 | 1 | -0.31 |
| area | 0.14 | 1 | 0.97 | -0.33 |
| biomass | 1 | 0.14 | 0.12 | -0.11 |

**OA1**

| | biomass | area | shape | enn |
|---|---|---|---|---|
| enn | 0.07 | -0.29 | -0.25 | 1 |
| shape | 0.02 | 0.85 | 1 | -0.25 |
| area | -0.1 | 1 | 0.85 | -0.29 |
| biomass | 1 | -0.1 | 0.02 | 0.07 |

**OA2&3**

| | biomass | area | shape | enn |
|---|---|---|---|---|
| enn | 0.05 | -0.29 | -0.28 | 1 |
| shape | 0.05 | 0.85 | 1 | -0.28 |
| area | 0.09 | 1 | 0.85 | -0.29 |
| biomass | 1 | 0.09 | 0.05 | 0.05 |

**Figure A2.** Principal component analysis (PCA) and Spearman correlation matrices showing correlations between patch metrics and mean aboveground biomass prior to charcoal production for charcoal sites larger than 1 ha detected through remote sensing. CB-villages are those villages under community-based natural resources management (CBNRM) and OA-villages are those under open access. We observe strong correlations between patch metrics and weak correlations between patch metrics and mean aboveground biomass prior to charcoal production.

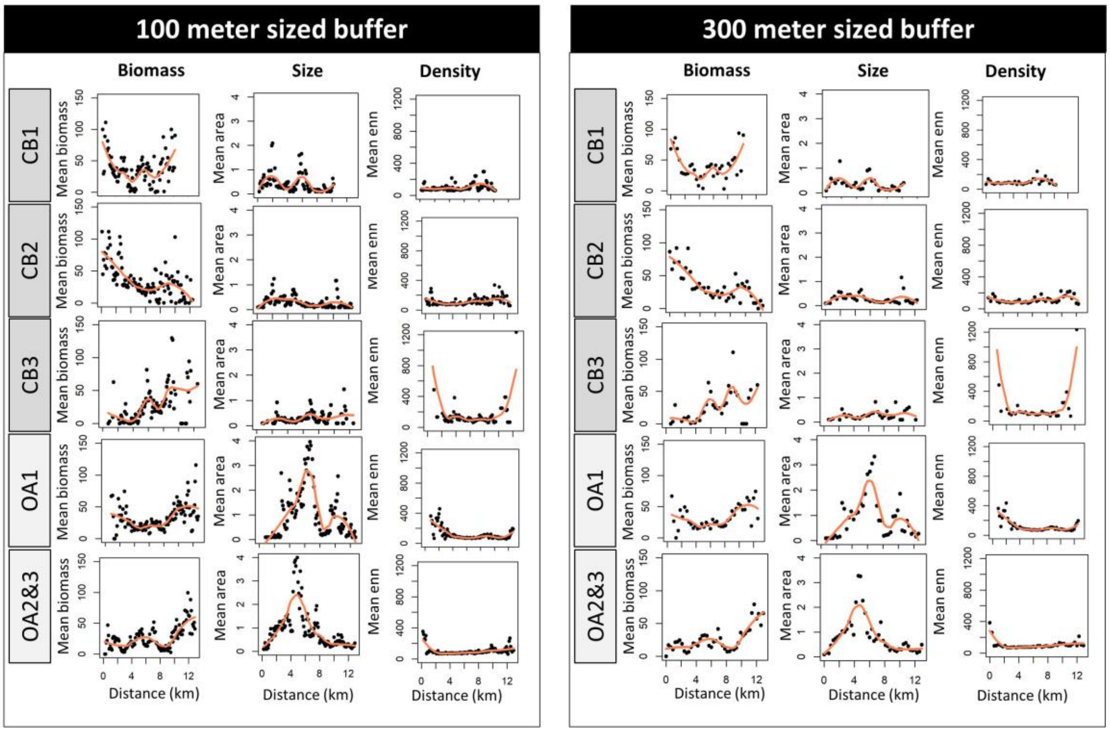


**Figure A3.** Sensitivity analysis to assess the effect of buffer width on the trends observed for mean aboveground biomass prior to charcoal production patch area (i.e., patch size) and Euclidean nearest-neighbor distance (ENN) (i.e., density of patches) of charcoal sites with distance from the village center, using two buffer sizes, namely 100 m and 300 m. OA = villages under open access and CB = villages under community-based natural resources management (CBNRM). OA2 and OA3 are located within the same village boundary, as OA3 had only just received the status of village at the time of this study and no formal boundary of the village had been determined.

## Tables:

**Table A1.** Statistical test results for one way Kruskal-Wallis ANOVA for patch area of charcoal sites between the six study villages. CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference. NA- refers to not applicable. Descriptions of the patch metrics can be found in Table 1 and the results are visualized in Fig. 4 of the main article. * = p-value < 0.05, ** = p-value < 0.005, *** = p-value < 0.0005.

| | **CB1** | **CB2** | **CB3** | **OA1** |
|---|---|---|---|---|
| **CB2** | $X^2_{(1, N = 904)} = 2.9428$, P-value = 0.0863 | NA | NA | NA |
| **CB3** | $X^2_{(1, N = 735)} = 4.4454$, P-value = 0.0350* | $X^2_{(1, N = 1031)} = 0.4398$, P-value = 0.5072 | NA | NA |
| **OA1** | $X^2_{(1, N = 2118)} = 16.2963$, P-value < 0.0001*** | $X^2_{(1, N = 2414)} = 58.3335$, P-value < 0.0001*** | $X^2_{(1, N = 2245)} = 55.4827$, P-value < 0.0001*** | NA |
| **OA2&3** | $X^2_{(1, N = 3339)} = 14.2391$, P-value = 0.0002*** | $X^2_{(1, N = 3635)} = 58.4396$, P-value < 0.0001*** | $X^2_{(1, N = 3466)} = 54.3932$, P-value < 0.0001*** | $X^2_{(1, N = 4849)} = 0.9406$, P-value = 0.3321 |

**Table A2.** An overview of the p-values of the differences found between the patch shape of charcoal sites in the six study villages, using the Kruskal-Wallis ANOVA. CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference. Descriptions of the network metrics can be found in Table 1 and the results are visualized in Fig. 4 of the main article. * = p-value < 0.05, ** = p-value < 0.005, *** = p-value < 0.0005.

| | **CB1** | **CB2** | **CB3** | **OA1** |
|---|---|---|---|---|
| **CB2** | $X^2_{(1, N = 904)} = 4.3588$, P-value = 0.0368* | NA | NA | NA |
| **CB3** | $X^2_{(1, N = 735)} = 4.3304$, P-value = 0.0374* | $X^2_{(1, N = 1031)} = 0.0392$, P-value = 0.8430 | NA | NA |
| **OA1** | $X^2_{(1, N = 2118)} = 9.5649$, P-value = 0.0020** | $X^2_{(1, N = 2414)} = 49.5362$, P-value < 0.0001*** | $X^2_{(1, N = 2245)} = 40.5272$, P-value < 0.0001*** | NA |
| **OA2&3** | $X^2_{(1, N = 3339)} = 8.8469$, P-value = 0.0029** | $X^2_{(1, N = 3635)} = 53.2801$, P-value < 0.0001*** | $X^2_{(1, N = 3466)} = 42.6659$, P-value < 0.0001*** | $X^2_{(1, N = 4849)} = 0.1588$, P-value = 0.6903 |

**Table A3.** An overview of the p-values of the differences found between the Euclidean nearest-neighbor index of charcoal sites in the six study villages, using the Kruskal Wallis ANOVA. CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference. Descriptions of the network metrics can be found in Table 1 and the results are visualized in Fig. 4 of the main article. * = p-value < 0.05, ** = p-value < 0.005, *** = p-value < 0.0005.

| | **CB1** | **CB2** | **CB3** | **OA1** |
|---|---|---|---|---|
| **CB2** | $X^2_{(1, N = 904)} = 3.0191$, P-value = 0.08229 | NA | NA | NA |
| **CB3** | $X^2_{(1, N = 735)} = 8.0877$, P-value = 0.0045** | $X^2_{(1, N = 1031)} = 2.5525$, P-value = 0.1101 | NA | NA |
| **OA1** | $X^2_{(1, N = 2118)} = 6.1833$, P-value = 0.0129* | $X^2_{(1, N = 2414)} = 34.0386$, P-value < 0.0001*** | $X^2_{(1, N = 2245)} = 44.5914$, P-value < 0.0001*** | NA |
| **OA2&3** | $X^2_{(1, N = 3339)} = 4.7013$, P-value = 0.0301* | $X^2_{(1, N = 3635)} = 32.1282$, P-value < 0.0001*** | $X^2_{(1, N = 3466)} = 43.5152$, P-value < 0.0001*** | $X^2_{(1, N = 4849)} = 0.6895$, P-value = 0.4063 |

**Table A4.** An overview of the p-values of the differences found between the distributions of the patch area of charcoal sites in the six study villages, using the two-sample Kolmogorov-Smirnov test. CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference. Descriptions of the network metrics can be found in Table 1 and the results are visualized in Fig. 4 of the main article. * = p-value < 0.05, ** = p-value < 0.005, *** = p-value < 0.0005.

| | **CB1** | **CB2** | **CB3** | **OA1** |
|---|---|---|---|---|
| **CB2** | D-statistic = 0.0681,<br>P-value = 0.3065 | NA | NA | NA |
| **CB3** | D-statistic = 0.1038,<br>P-value = 0.0429* | D-statistic = 0.0000,<br>P-value = 0.1101 | NA | NA |
| **OA1** | D-statistic = 0.1354,<br>P-value = 0.0001*** | D-statistic = 0.1915,<br>P-value < 0.0001*** | D-statistic = 0.1779,<br>P-value < 0.0001*** | NA |
| **OA2&3** | D-statistic = 0.1079,<br>P-value = 0.0032** | D-statistic = 0.1915,<br>P-value < 0.0001*** | D-statistic = 0.1856,<br>P-value < 0.0001*** | D-statistic = 0.0452,<br>P-value = 0.0192* |

**Table A5.** An overview of the p-values of the differences found between the distributions of the patch shape of charcoal sites in the six study villages, using the two-sample Kolmogorov-Smirnov test. CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference. Descriptions of the network metrics can be found in Table 1 and the results are visualized in Fig. 4 of the main article. * = p-value < 0.05, ** = p-value < 0.005, *** = p-value < 0.0005.

| | **CB1** | **CB2** | **CB3** | **OA1** |
|---|---|---|---|---|
| **CB2** | D-statistic = 0.1059,<br>P-value = 0.0216* | NA | NA | NA |
| **CB3** | D-statistic = 0.1141,<br>P-value = 0.0192* | D-statistic = 0.0000,<br>P-value = 1.0000 | NA | NA |
| **OA1** | D-statistic = 0.1117,<br>P-value = 0.0030** | D-statistic = 0.1576,<br>P-value < 0.0001*** | D-statistic = 0.1640,<br>P-value < 0.0001*** | NA |
| **OA2&3** | D-statistic = 0.0992,<br>P-value = 0.0087* | D-statistic = 0.1576,<br>P-value < 0.0001*** | D-statistic = 0.1687,<br>P-value < 0.0001*** | D-statistic = 0.0348,<br>P-value = 0.1183 |

**Table A6.** An overview of the p-values of the differences found between the distributions of the Euclidean nearest-neighbor distance of charcoal sites in the six study villages, using the two-sample Kolmogorov-Smirnov test. CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference. Descriptions of the network metrics can be found in Table 1 and the results are visualized in Fig. 4 of the main article. * = p-value < 0.05, ** = p-value < 0.005, *** = p-value < 0.0005.

| | **CB1** | **CB2** | **CB3** | **OA1** |
|---|---|---|---|---|
| **CB2** | D-statistic = 0.0573,<br>P-value = 0.5221 | NA | NA | NA |
| **CB3** | D-statistic = 0.1239,<br>P-value = 0.0084* | D-statistic = 0.0000,<br>P-value = 1.0000 | NA | NA |
| **OA1** | D-statistic = 0.0740,<br>P-value = 0.1157 | D-statistic = 0.1257,<br>P-value < 0.0001*** | D-statistic = 0.1752,<br>P-value < 0.0001*** | NA |
| **OA2&3** | D-statistic = 0.0689,<br>P-value = 0.1451 | D-statistic = 0.1257,<br>P-value < 0.0001*** | D-statistic = 0.1257,<br>P-value < 0.0001*** | D-statistic = 0.0159,<br>P-value = 0.9375 |

# Appendix Chapter 6

## Appendix A

Sections of the livelihood survey used for this paper.

### 9. Interactions with other charcoal producers

<table>
<tr>
<td>9.1 Do you work together with other charcoal producers? (Why? / Why not?)<br><br>Yes / No</td>
<td colspan="2">9.2 With whom of the charcoal producers do you prefer to work? (Why them?)<br>____________________<br>____________________<br>____________________<br>____________________<br>____________________<br>____________________</td>
</tr>
<tr>
<td>9.3 Are there other charcoal producers you work with?<br><br>Yes / No</td>
<td colspan="2">9.4 Who are the other charcoal producers you work with?<br>____________________<br>____________________<br>____________________<br>____________________<br>____________________<br>____________________</td>
</tr>
<tr>
<td>9.5 How many charcoal producers do you work with in total?<br><br>__________<br>producers</td>
<td>9.6 How many times do you generally see them per week?<br><br>**→ Indicate with a number in 7.2 and 7.4**</td>
<td>9.7 Whom of these producers are your family or neighbors (indicate with F or N)?<br>____________________<br>____________________<br>____________________<br>____________________</td>
</tr>
<tr>
<td>9.8 How did you meet the</td>
<td colspan="2">9.9 With whom of the charcoal producers do you exchange skills and knowledge about charcoal production?</td>
</tr>
</table>

| | |
|---|---|
| charcoal producers you work with? | ____________________<br>____________________<br>____________________<br>____________________<br>____________________ |
| 9.10 With whom do you talk about the state of the forest and its species?<br>____________________<br>____________________<br>____________________<br>____________________ | 9.11 Which other topics do you talk about together? |
| 9.12 Whom would you be willing to help out financially?<br>____________________<br>____________________ | |

## 11. Interaction with village council

| | | | |
|---|---|---|---|
| 11.1 Do you interact with members of the village council? (Why? / Why not?)<br>Yes / No | 11.2 *If 11.1 = Yes*; Whom from the village council do you interact with?<br>____________________<br>____________________<br>____________________<br>____________________<br>____________________ | | |
| 11.3 How many members of the village council do you interact with in total? | 11.4 How many times per month do you interact with these | 11.5 Which topics do you talk about with members of | 11.6 Whom of the village council are your family or neighbors (indicate with F or N)?<br>____________________ |

| | | | |
|---|---|---|---|
| ____________<br>members | council members?<br>→ **Indicate with a number in 11.2** | the village council? | ____________________<br>____________________<br>____________________ |
| 11.7 Whom of the village council decides over charcoal production within the village forest?<br>____________________<br>____________________<br>____________________ | | | 11.8 How many times per month do you interact with the members of the village council that decide over charcoal production within the forest?<br>→ **Indicate per person in 11.7** |
| 11.9 Would you get in contact with village council members if illegal charcoal production takes place in the village forest? (Why? / Why not?)<br>Yes / No | 11.10 *If 11.9 = Yes*; Who of the village council would you contact to notify them about illegal charcoal production in the village forest?<br>____________________<br>____________________<br>____________________ | | |
| 11.11 Can you tell us how you would be able to obtain (more) land for farming or forestry? | 11.12 Who of the village council can allocate land for farming or forestry?<br>____________________<br>____________________<br>____________________<br>____________________ | | 11.13 How regularly do you interact with the members of the village council that have the right to allocate land for farming or forestry?<br>→ **Indicate per person in 11.12** |

## 13. Interaction with the Kilosa District Government

| | |
|---|---|
| 13.1 Do you interact with members of district government? (Why? / Why not?)<br>Yes / No | 13.2 Whom from the district government do you interact with?<br>____________________<br>____________________ |

| | | |
|---|---|---|
| | ______________________________<br>______________________________<br>______________________________ | |
| 13.3 How many members of the district government do you interact with in total?<br>__________<br>members | 13.4 How many times per year do you interact with these district government members?<br>→ **Indicate with a number in 13.2** | 13.5 Which topics do you talk with them about? |
| 13.6 Would you get in contact with district officials to acquire information about rules and regulations for charcoal production? (Why? / Why not?)<br>Yes / No | 13.7 *If 13.6 = Yes*; Which district official(s) would you contact to acquire information about rules and regulations for charcoal production?<br>______________________________<br>______________________________<br>______________________________ | |
| 13.8 Would you get in contact with district officials if illegal charcoal production takes place in the village forest? (Why? / Why not?)<br>Yes / No | 13.9 *If 13.8 = Yes*; Which district official(s) would you contact to notify them about illegal charcoal production in the village forest?<br>______________________________<br>______________________________<br>______________________________ | |

## 14. Interaction with Tanzania Forest Service

| | |
|---|---|
| 14.1 Do you interact with members of Tanzania Forest Service? (Why? / Why not?)<br>Yes / No | 14.2 Whom from Tanzania Forest Service do you interact with?<br>______________________________<br>______________________________<br>______________________________<br>______________________________ |

| | | |
|---|---|---|
| | ______________________________ | |
| 14.3 How many officials of the Tanzania Forest Service do you interact with in total?<br>____________<br>members | 14.4 How many times per year do you interact with these officials of Tanzania Forest Service?<br>→ **Indicate with a number in 14.2** | 14.5 Which topics do you talk with them about? |
| 14.6 Would you get in contact with officials of Tanzania Forest Service to acquire information about rules and regulations for charcoal production? (Why? / Why not?)<br>Yes / No | 14.7 *If 14.6 = Yes*; Which Tanzania Forest Service official(s) would you contact to acquire information about rules and regulations for charcoal production?<br>______________________________<br>______________________________<br>______________________________ | |
| 14.8 Would you get in contact with Tanzania Forest Service if illegal charcoal production takes place in the village forest? (Why? / Why not?)<br>Yes / No | 14.9 *If 14.8 = Yes*; Which Tanzania Forest Service officials would you contact to notify them about illegal charcoal production in the village forest?<br>______________________________<br>______________________________<br>______________________________ | |

## 15. Associations, life goals and support

| | | |
|---|---|---|
| 15.1 Are you a member of a charcoal producer association? (Why? / Why not?)<br>Yes / No | 15.2 *If 15.1 = Yes*; Which tasks do you have in the charcoal producer association? | 15.3 Do you take part in the decision making process of the charcoal producer association? (In what way?)<br>Yes / No |
| 15.4 Are you a member of another community association? (Why / Why not?)<br>Yes / No | 15.5 If 15.4 = Yes; Which community association is this and what are your tasks? | 15.6 Do you take part in the conventional decision making process within the village? (In what way?)<br>Yes / No |

| | | |
|---|---|---|
| 15.7 How many associations are you a member of in total?<br>___________________<br>associations | 15.8 Do you feel like you have similar goals in life as other villagers (Why? / Why not?)<br>Yes / No | 15.9 Do you feel supported by other villagers (Why? / Why not?)<br>Yes / No |
| 15.10 Do you feel supported by the village committee (Why / Why not?)<br>Yes / No | 15.11 Do you feel supported by TFCG (Why? / Why not?)?<br>Yes / No | 15.12 Do you feel supported by the district government? (Why? / Why not?)<br>Yes / No |
| 15.13 Do you feel supported by the Tanzania Forest Service?<br>Yes / No | 15.14 *In your view*; How can the village committee and TFCG support increase their support to you in the future? | 15.15 *In your view*; How can the district government and Tanzania Forest Service increase their support to you in the future? |

## Appendix B

### Informed consent for participation in the research project

*Social capital of charcoal producers and its impact on other livelihood capitals*

*Responsible for research project*: Maria J. Santos, Hanneke van 't Veen
*Institution*: Winterthurerstrasse 190, 8057 Zürich, Switzerland
*Contact Information*: Maria J. Santos, Department of Geography Y25-J-68, Winterthurerstrasse 190, 8057 Zürich, Switzerland

### Information on the research project

Charcoal producers have different livelihood resources they depend upon, such as (i) the income they derive from charcoal production (i.e. financial capital), (ii) the woody biomass resources they depend upon for production (i.e. natural capital), (iii) their skills and knowledge of charcoal production (i.e. human capital), (iv) their access to housing and infrastructure (i.e. physical capital), and finally (v) their social networks (i.e. social capital) (FAO 2017). In this study we are interested in how the social networks and interactions of charcoal producers influence the amount of charcoal they produce, their income, their knowledge and charcoal producer skills and also their overall assets. This will provide an insight in the importance of social networks and interactions of charcoal producers in pursuing their livelihoods. By comparing the livelihood resources of charcoal producers between villages that are involved in the TFCG project on community charcoal production and villages that are not involved in this project, we will gain a better understanding of the impact of these types of projects on the lives of charcoal producers. By including information about the formal and informal governance of charcoal production by institutions, including the village councils, TFCG, the district of Kilosa and Tanzania Forest Services, we gain a better understanding of the influence of these institutions on charcoal producer livelihoods and charcoal production in general. This data gathered during this project can be used to improve policies on charcoal production in Tanzania and around the world.

This PhD project for which the data will be acquired is funded by the University Research Priority Program of Global Change and Biodiversity (URPP-GCB) of the University of Zurich in Switzerland.

### Taking part in the study

Your participation in this research project consists of an interview that lasts about two hours and will be audio-recorded. The interviewers will also note down some of your answers to the questions on a survey sheet. You will be asked questions on the topic of your livelihoods, including questions about i) charcoal production, ii) the income you derive from charcoal production, iii) farming, iv) trees on your land, v) the forest, vi) your interactions with other charcoal producers and members of the village council, and v) the access you have to housing and infrastructure.

### Withdrawal from the participation or the consent

The participation in this research project is voluntary. You have at all times the right to withdraw from participating in the research project, without having to state the reason. You also have the right to withdraw your consent which will result in your personal information being removed so that it cannot be linked to you anymore.

**Data protection, confidentiality and future use**

The data collected in the research project *Social capital of charcoal producers and its impact on other livelihood capitals* will only be used for strictly scientific research purposes. Your name or other identifying information will not be revealed in any publication or handed to third parties, and will be kept confidential.

Your contribution (the audio-recorded interviews and hand-written survey sheets) will be stored for long-term preservation in the secure environment of the national data archive of FORS, Swiss Centre of Expertise in the Social Sciences, funded by the State Secretariat for Education, Research, and Innovation. Your information will be de-identified.

Your de-identified information may be made available to accredited researchers and students affiliated with an institution of higher learning for secondary research with prior agreement from the primary research team, only after they have signed a data protection contract obliging them to refrain from trying to identify persons and requiring them to use the data in a way that respects your confidentiality and within the framework of existing data protection legislation.

**Consent**

I have read and understood the information in this form, or it has been read to me. I have been able to ask questions about the research project *Social capital of charcoal producers and its impact on other livelihood capitals* and these have been answered to my satisfaction.

I consent freely to participating in the research project and I give permission for my contribution to be stored in a secure environment and to be made available in de-identified form for future research and learning.

Signatures

Name of participant Signature Date

Name of researcher Signature Date

The participant has received a signed copy of the informed consent form.

# Appendix C

**Table C1.** An overview of the p-values and, in case of per-node metrics, Kruskal-Wallis Chi-squared values for differences found in the bonding of charcoal producers social networks between the six study villages. We used the Kruskal Wallis one way analysis of variance for per-node metrics (degree, betweenness and closeness) and the pairwise t-test for per-network metrics (diameter, distance and reciprocity). CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference, which are highlighted in red. Descriptions of the network metrics can be found in Table 3 and the results are visualized in Fig. 3 and Fig. 4 of the main article.

**Bonding social networks**

**Degree**

| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
|---|---|---|---|---|---|
| **CB2** | $X^2_{(1, x = 176)}$ = 0.18<br>P-value = 0.6702 | - | - | - | - |
| **CB3** | $X^2_{(1, x = 180)}$ = 0.56<br>P-value = 0.4557 | $X^2_{(1, x = 140)}$ =1.05<br>P-value = 0.3066 | - | - | - |
| **OA1** | $X^2_{(1, x = 175)}$ =10.68<br>P-value = 0.0011 | $X^2_{(1, x = 135)}$ =5.65<br>P-value = 0.0174 | $X^2_{(1, x = 139)}$ =13.73<br>P-value = 0.0002 | - | - |
| **OA2** | $X^2_{(1, x = 143)}$ =13.89<br>P-value = 0.0002 | $X^2_{(1, x = 103)}$ =8.89<br>P-value = 0.0029 | $X^2_{(1, x = 107)}$ =15.64<br>P-value = 8e-05 | $X^2_{(1, x = 102)}$ =2.13<br>P-value = 0.1441 | - |
| **OA3** | $X^2_{(1, x = 148)}$ =17.33<br>P-value = 3e-05 | $X^2_{(1, x = 108)}$ =11.23<br>P-value = 0.0008 | $X^2_{(1, x = 112)}$ =18.38<br>P-value = 5e-05 | $X^2_{(1, x = 107)}$ =3.50<br>P-value = 0.0612 | $X^2_{(1, x = 75)}$ =0.064<br>P-value = 0.7989 |

**Betweenness**

| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
|---|---|---|---|---|---|
| **CB2** | $X^2_{(1, x = 176)}$ =0.02<br>P-value = 0.8764 | - | - | - | - |
| **CB3** | $X^2_{(1, x = 180)}$ =0.02<br>P-value = 0.8861 | $X^2_{(1, x = 140)}$ =0.09<br>P-value = 0.7621 | - | - | - |
| **OA1** | $X^2_{(1, x = 175)}$ =7.19<br>P-value = 0.0073 | $X^2_{(1, x = 135)}$ =6.31<br>P-value = 0.0120 | $X^2_{(1, x = 139)}$ =8.59<br>P-value = 0.0034 | - | - |
| **OA2** | $X^2_{(1, x = 143)}$ =7.00<br>P-value = 0.0081 | $X^2_{(1, x = 103)}$ =6.89<br>P-value = 0.0087 | $X^2_{(1, x = 107)}$ =8.34<br>P-value = 0.0039 | $X^2_{(1, x = 102)}$ =1.60<br>P-value = 0.2061 | - |
| **OA3** | $X^2_{(1, x = 148)}$ =5.94<br>P-value = 0.0148 | $X^2_{(1, x = 108)}$ =5.56<br>P-value = 0.0183 | $X^2_{(1, x = 112)}$ =7.10<br>P-value = 0.0077 | $X^2_{(1, x = 107)}$ =0.27<br>P-value = 0.6036 | $X^2_{(1, x = 75)}$ =0.88<br>P-value = 0.3496 |

**Closeness**

| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
|---|---|---|---|---|---|
| **CB2** | $X^2_{(1, x = 176)}$ = 125.47<br>P-value = 4e-29 | - | - | - | - |
| **CB3** | $X^2_{(1, x = 180)}$ =230.03<br>P-value = 4e-30 | $X^2_{(1, x = 140)}$ =32.93<br>P-value = 10e-09 | - | - | - |
| **OA1** | $X^2_{(1, x = 175)}$ =125.14<br>P-value = 5e-29 | $X^2_{(1, x = 135)}$ =0.031<br>P-value = 0.8603 | $X^2_{(1, x = 139)}$ =11.76<br>P-value = 0.0006 | - | - |
| **OA2** | $X^2_{(1, x = 143)}$ =79.93<br>P-value = 4e-19 | $X^2_{(1, x = 103)}$ =69.97<br>P-value = 6e-17 | $X^2_{(1, x = 107)}$ =71.69<br>P-value = 3e-17 | $X^2_{(1, x = 102)}$ =71.99<br>P-value = 2e-17 | - |
| **OA3** | $X^2_{(1, x = 148)}$ =88.15<br>P-value = 6e-21 | $X^2_{(1, x = 108)}$ =76.11<br>P-value = 3e-18 | $X^2_{(1, x = 112)}$ =78.07<br>P-value = 1e-20 | $X^2_{(1, x = 107)}$ =77.90<br>P-value = 1e-18 | $X^2_{(1, x = 75)}$ =58.08<br>P-value = 3e-14 |

**Diameter (Bootstrapped)**

| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
|---|---|---|---|---|---|
| **CB2** | P-value = 2e-16 | - | - | - | - |
| **CB3** | P-value = 2e-16 | P-value = 2e-16 | - | - | - |
| **OA1** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - | - |
| **OA2** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - |
| **OA3** | P-value = 2e-16 | P-value = 0.3000 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 |

**Distance (Bootstrapped)**

| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
|---|---|---|---|---|---|
| **CB2** | P-value = 2e-16 | - | - | - | - |
| **CB3** | P-value = 2e-16 | P-value = 2e-16 | - | - | - |
| **OA1** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - | - |
| **OA2** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - |
| **OA3** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 |

**Reciprocity (Bootstrapped)**

| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
|---|---|---|---|---|---|
| **CB2** | P-value = 0.0330 | - | - | - | - |
| **CB3** | P-value = 0.1190 | P-value = 1.0000 | - | - | - |
| **OA1** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - | - |
| **OA2** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 1.0000 | - |
| **OA3** | P-value = 5e-07 | P-value = 1e-14 | P-value = 9e-13 | P-value = 2e-16 | P-value = 2e-16 |

**Table C2.** An overview of the p-values and, in case of per-node metrics, Kruskal-Wallis Chi-squared values for differences found in the linking of charcoal producer social networks between the six study villages. We used the Kruskal Wallis one way analysis of variance for per-node metrics (degree, betweenness and closeness) and the pairwise t-test for per-network metrics (diameter, distance and reciprocity). CB = Villages involved in the TTCS project. OA = Villages under open access. The p-values <0.05 reflect a significant difference, which are highlighted in red. Descriptions of the network metrics can be found in Table 3 and the results are visualized in Fig. 4 and Fig. 5 of the main article.

| **Linking social networks** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Degree** | | | | | | **Betweenness** | | | | | |
| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** | | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
| **CB2** | $X^2_{(1, x = 176)}$ =3.23 P-value = 0.0720 | - | - | - | - | **CB2** | $X^2_{(1, x = 176)}$ =0.88 P-value = 0.3469 | - | - | - | - |
| **CB3** | $X^2_{(1, x = 180)}$ =0.07 P-value = 0.7940 | $X^2_{(1, x = 140)}$ =2.11 P-value = 0.1468 | - | - | - | **CB3** | $X^2_{(1, x = 180)}$ =0.75 P-value = 0.3881 | $X^2_{(1, x = 140)}$ =0.01 P-value = 0.9412 | - | - | - |
| **OA1** | $X^2_{(1, x = 175)}$ =7.26 P-value = 0.0070 | $X^2_{(1, x = 135)}$ =1.17 P-value = 0.2783 | $X^2_{(1, x = 139)}$ =5.55 P-value = 0.0185 | - | - | **OA1** | $X^2_{(1, x = 175)}$ =3.38 P-value = 0.0661 | $X^2_{(1, x = 135)}$ =1.62 P-value = 0.2026 | $X^2_{(1, x = 139)}$ =1.68 P-value = 0.1944 | - | - |
| **OA2** | $X^2_{(1, x = 143)}$ =3.70 P-value = 0.0545 | $X^2_{(1, x = 103)}$ =0.26 P-value = 0.6085 | $X^2_{(1, x = 107)}$ =2.57 P-value = 0.1090 | $X^2_{(1, x = 102)}$ =0.19 P-value = 0.6613 | - | **OA2** | $X^2_{(1, x = 143)}$ =2.19 P-value = 0.1389 | $X^2_{(1, x = 103)}$ =1.05 P-value = 0.3060 | $X^2_{(1, x = 107)}$ =1.09 P-value = 0.2971 | $X^2_{(1, x = 102)}$ =0.00 P-value = 1.000 | - |
| **OA3** | $X^2_{(1, x = 148)}$ =4.40 P-value = 0.0359 | $X^2_{(1, x = 108)}$ =0.04 P-value = 0.8384 | $X^2_{(1, x = 112)}$ =2.93 P-value = 0.0868 | $X^2_{(1, x = 107)}$ =0.32 P-value = 0.3208 | $X^2_{(1, x = 75)}$ =0.21 P-value = 0.6496 | **OA3** | $X^2_{(1, x = 148)}$ =3.67 P-value = 0.0553 | $X^2_{(1, x = 108)}$ =1.77 P-value = 0.1838 | $X^2_{(1, x = 112)}$ =1.83 P-value = 0.1759 | $X^2_{(1, x = 107)}$ =0.00 P-value = 1.000 | $X^2_{(1, x = 75)}$ =0.00 P-value = 1.000 |
| **Closeness** | | | | | | **Diameter (Bootstrapped)** | | | | | |
| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** | | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
| **CB2** | $X^2_{(1, x = 176)}$ =79.89 P-value = 4e-19 | - | - | - | - | **CB2** | P-value = 2e-16 | - | - | - | - |
| **CB3** | $X^2_{(1, x = 180)}$ =85.49 P-value = 2e-20 | $X^2_{(1, x = 140)}$ =67.68 P-value = 2e-16 | - | - | - | **CB3** | P-value = 2e-16 | P-value = 2e-16 | - | - | - |
| **OA1** | $X^2_{(1, x = 175)}$ =84.12 P-value = 5e-20 | $X^2_{(1, x = 135)}$ =77.72 P-value = 1e-18 | $X^2_{(1, x = 139)}$ =75.86 P-value = 2e-18 | - | - | **OA1** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - | - |
| **OA2** | $X^2_{(1, x = 143)}$ =63.27 P-value = 2e-15 | $X^2_{(1, x = 103)}$ =59.76 P-value = 1e-14 | $X^2_{(1, x = 107)}$ =58.02 P-value = 2e-14 | $X^2_{(1, x = 102)}$ =55.78 P-value = 8e-14 | - | **OA2** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - |
| **OA3** | $X^2_{(1, x = 148)}$ =85.26 P-value = 2e-20 | $X^2_{(1, x = 108)}$ =81.04 P-value = 2e-19 | $X^2_{(1, x = 112)}$ =70.42 P-value = 5e-17 | $X^2_{(1, x = 107)}$ =67.96 P-value = 2e-16 | $X^2_{(1, x = 75)}$ =57.16 P-value = 4e-14 | **OA3** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 5e-07 |
| **Distance (Bootstrapped)** | | | | | | **Reciprocity (Bootstrapped)** | | | | | |
| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** | | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
| **CB2** | P-value = 2e-16 | - | - | - | - | **CB2** | P-value = 2e-16 | - | - | - | - |
| **CB3** | P-value = 2e-16 | P-value = 2e-16 | - | - | - | **CB3** | P-value = 2e-16 | P-value = 1.000 | - | - | - |
| **OA1** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - | - | **OA1** | P-value = 2e-16 | P-value = 1.000 | P-value = 0.9200 | - | - |
| **OA2** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | - | **OA2** | P-value = 2e-16 | P-value = 1.000 | P-value = 0.9200 | P-value = 1.000 | - |
| **OA3** | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | P-value = 2e-16 | **OA3** | P-value = 2e-16 | P-value = 1.000 | P-value = 0.9200 | P-value = 1.000 | P-value = 1.000 |

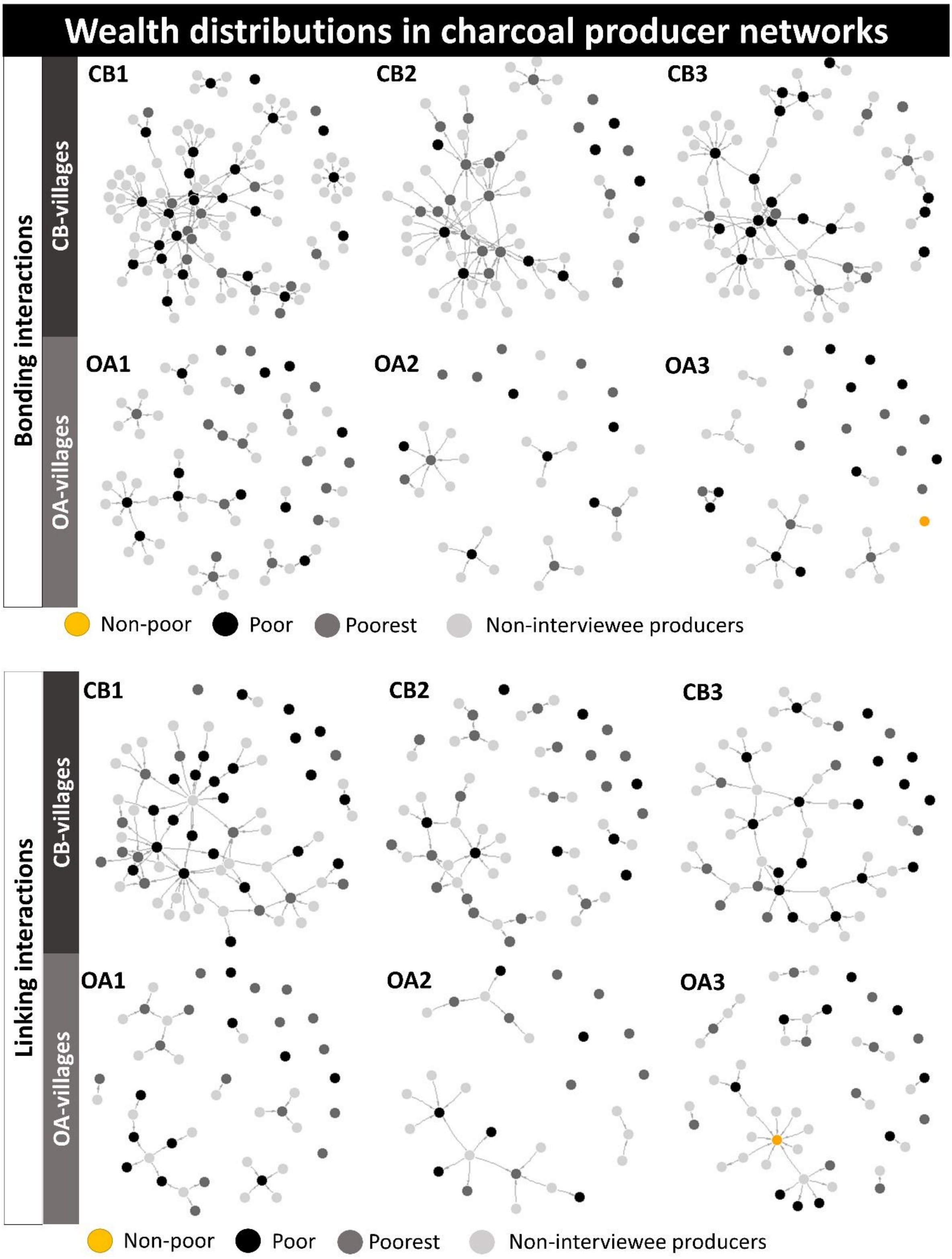


**Figure C1.** Linking social networks, reflecting the interactions of charcoal producers with members of the Village Council in three villages in which the community-based natural resource management project Transforming Tanzania's Charcoal Sector (TTCS) has been introduced (CB1-3) and three open access villages (OA1-3). Nodes are colored based on their wealth class.

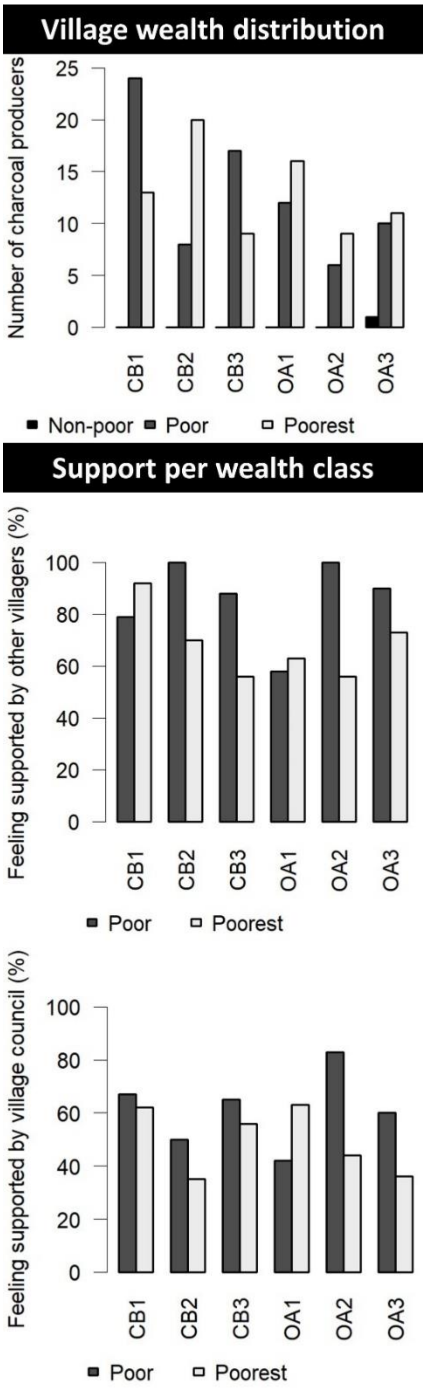


**Figure C2.** *Top panel*: Wealth distribution of the interviewed charcoal producers. *Bottom panel*: Overview the percentage of charcoal producers that feel supported by (i) their fellow villagers, and (ii) members of their Village Council per wealth glass (poor and poorest) in three CBNRM villages (CB1-CB3) in which the community-based natural resource management project Transforming Tanzania’s Charcoal Sector (TTCS) and three open access villages (OA1-OA3).

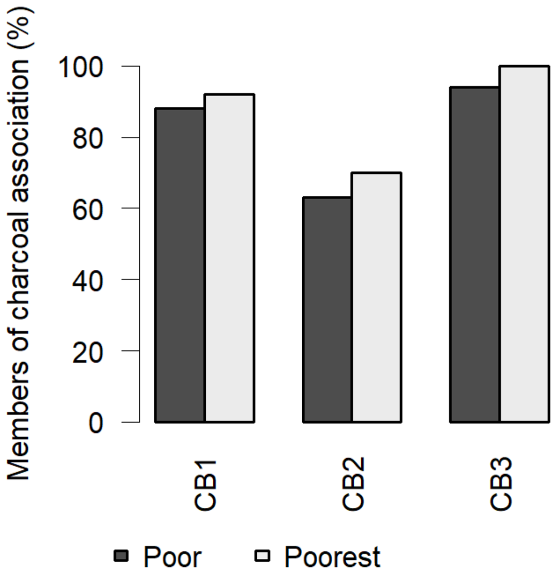


**Figure C3.** Overview the percentage of charcoal producers that are a member of a charcoal producer association per wealth glass (poor and poorest) in three CBNRM villages (CB1-CB3) in which the community-based natural resource management project Transforming Tanzania's Charcoal Sector (TTCS).

# Appendix A

## Original surveys used to acquire data for this study:

Project: Understanding the impact of social capital on the livelihoods of charcoal producers

### 1. Personal data, background and setting

<table>
<tr><td colspan="2">1.1 Charcoal producer name:<br>________________________</td><td>1.2 Gender:<br>Male / Female</td><td>1.3 Education level:<br>○ Formal education<br>○ No formal education</td></tr>
<tr><td colspan="2">1.4 Household size:<br>1 / 2 / 3 / 4 / 5 / 6 / 7 / 8 / 9 / 10 / 11</td><td>1.5 Do you need a permit for charcoal production?</td><td>1.6 <i>If 1.5 = yes</i>; Are you in possession of a charcoal production permit?<br>Yes / No</td></tr>
<tr><td>1.7 How did you become a charcoal producer?</td><td>1.8 What is the reason you became a charcoal producer?</td><td>1.9 Are you satisfied with your work as a charcoal producer? (Why?/Why not?)</td><td>1.10 Would you like to remain a charcoal producer in the future? (Why?/Why not?)</td></tr>
<tr><td colspan="2">1.11 Do you produce charcoal from trees in the village forest? (Why these trees?)<br>Yes / No</td><td>1.12 Do you produce charcoal from farming residue or trees on the land on which you practice agriculture? (Why / Why not?)<br>Yes / No</td><td>1.13 Do you produce charcoal full-time or part-time?<br>○ Full-time<br>○ Part-time</td></tr>
</table>

### 2. Farming

<table>
<tr><td>2.1 <i>If 1.10 = farming</i>; Who owns the land that you farm?<br>○ Yourself<br>○ A family member<br>○ Village government<br>○ National government<br>○ Company<br>○ Other: ________________</td><td>2.2 What is the approximate size of the land that you farm?<br>________________________</td><td colspan="2">2.3 Do you have a formal certificate of ownership or tenure for your land?<br>Yes / No</td></tr>
<tr><td>2.4 Is your tenure or ownership certificate limited for a certain period or practice?<br>Yes / No</td><td>2.5 How long have you been a farmer?<br>____________________ years</td><td colspan="2">2.6 How did you acquire your farming skills?</td></tr>
<tr><td>2.7 Did you receive any training in agriculture?<br>Yes / No</td><td>2.8 <i>If 2.7 = Yes</i>; What training in agriculture did you receive and by whom? (Indicate whom below)<br>________________________<br>________________________<br>________________________<br>________________________</td><td>2.9 Do you share your knowledge about agriculture with others?<br>Yes / No</td><td>2.10 <i>If 2.9 = yes</i>; What knowledge about agriculture do you share with others?</td></tr>
</table>

| | | |
|---|---|---|
| 2.11 *If 2.9 = Yes*; With whom do you share your knowledge about agriculture?<br>○ Family<br>○ Friends<br>○ Other farmers<br>○ Village council<br>○ Others: ________________ | 2.12 Has the way you farm your land changed over the past 5 years? (In what way?; yield, crops, climate, pests, diseases)<br>Yes / No | 2.13 How many of your family members help you farm?<br>___________________ members |
| 2.14 How much time do you devote to farming per day/week or in %?<br>_________________________ | 2.15 Which months of the year do you devote to farming?<br>______________________________<br>______________________________ | 2.16 Do you have enough time to produce charcoal and farm at the same time?<br>Yes / No |
| 2.17 Would you consider to plant trees specifically for charcoal production on your farm land?<br>Yes / No | 2.18 Under what circumstances would you consider planting trees for charcoal production on your farm land? | 2.18 Which trees would you be interested in planting on your farm land for charcoal production? (Why these trees?) |

## 3. Agroforestry (if 1.12 = Yes)

| | | |
|---|---|---|
| 3.1 How many trees do you have on your farm?<br>______________________ trees | 3.2 What do the trees on your farm provide you?<br>○ Fruit,<br>○ Shade<br>○ Firewood,<br>○ Charcoal<br>○ Medicine<br>○ Other: _________________ | 3.3 Do you sell products derived from the trees on your farm? (Why? / Why not?) |
| 3.4 *If 3.3 = Yes*; What do you invest the money in that you obtain by selling the products derived from the trees on your farm? | 3.5 Do you trade the products derived from the trees on your farm with your neighbors? (Why? / Why not?)<br>Yes / No | 3.6 How do you manage the trees on your farm? (Pruning, harvesting etc.) |
| 3.7 What part of the tree do you harvest on your farm? | 3.8 Do you plant new trees? (If yes, which kind and what for? If no, why not?)<br>Yes / No | 3.9 How many of your family members produce charcoal from the trees on your land?<br>___________________ members |
| 3.10 Do other people than your family produce charcoal from the trees on your land?<br>Yes / No | 3.11 Do you hire people to produce charcoal for you from the trees on your land? (Why? / Why not?)<br>Yes / No | 3.12 *If 3.11 = Yes*; How many people do you hire per year to produce charcoal for you from the trees on your land?<br>_____________________ people |

## 4. Data on charcoal production

| | | |
|---|---|---|
| 4.1 How many years of experience in charcoal production do you have?<br>____________________ years | 4.2 How do you decide, when and how much charcoal to produce? (wood availability, need for cash, off-season etc.) | 4.3 How many charcoal kilns do you make per month?<br>_____________________ kilns |
| 4.4 How many kilns do you make per year? | 4.5 How many months of the year do you produce charcoal? (Which months?) | 4.6 How big is the charcoal kiln you usually build? (Ask for ranges) |

| | | |
|---|---|---|
| _______________ kilns | ______________ months | _____________ length<br>_____________ width<br>_____________ height |
| 4.7 How much time does the process of charcoal production from cutting trees to collecting charcoal take?<br>_______________ days | 4.8 With how many people do you make a kiln?<br>______________ people | 4.9 What equipment do you use when producing charcoal? |

## 5. Sales and income

| | | |
|---|---|---|
| 5.1 What share of the wood you put into a kiln comes out as charcoal that can be sold?<br>_________________ | 5.2 How many bags of charcoal do you produce per kiln?<br>_______________ bags | 5.3 How much money do you make per bag of charcoal?<br>_______________ TZS |
| 5.4 What is the net amount of money you make per bag of charcoal? (considering sharing the revenue)<br>_______________ TZS | 5.5 Who do you sell the finished charcoal to?<br>○ Transporter<br>○ Middle man<br>○ Wholesaler<br>○ Directly to customers<br>○ Other: _______________ | 5.6 How do you know the person you are selling charcoal to? |
| 5.7 Which other activities are you involved in besides charcoal production?<br>- Farming<br>- Livestock keeping<br>- Business<br>- Others: ___________<br>_________________<br>_________________ | 5.8 How much income do you make from other activities per year?<br>_______________ TZS | 5.9 What do you use your income money for?<br>○ Food and housing<br>○ Clothing and furniture<br>○ Agricultural inputs<br>○ School fees<br>○ Health care<br>○ Others: ___________<br>_________________ |
| 5.10 How much taxes do you pay per bag?<br>________________ TZS<br>Give explanation, if you are not paying any tax<br>____________________ | 5.11 How much does a charcoal production permit cost you?<br>_______________ TZS | 5.12 Are you able to save money from the income you derive?<br>Yes / No |
| 5.13 *If 5.12 = Yes*; How much money do you save per year?<br>_______________ TZS | 5.14 *If 5.12 = Yes*; What do you use this money for?<br>○ Food and housing<br>○ Agricultural inputs<br>○ School fees<br>○ Health care<br>○ Others: ______________________________ | |

## 6. Health

| | | |
|---|---|---|
| 6.1 Does charcoal production pose a risk for your respiratory health (How?)<br>Yes / No | 6.2 Does charcoal production pose a risk for your physical health? (How?)<br>Yes / No | 6.3 Do you take any safety precautions? (Which?, Why? / Why not?)<br>Yes / No |

| | | |
|---|---|---|
| 6.4 Have you had any injuries from charcoal production? (Which?)<br>Yes / No | 6.5 *If 6.4 = Yes*; Can you tell us how you obtained this injury? | 6.6 *If 6.4 = Yes*; How long did your injury reduce your ability to work?<br>____________________________ |
| 6.7 Have you had any injuries from farming? (Which?)<br>Yes / No | 6.8 *If 6.7 = Yes*; Can you tell us how you obtained this injury? | 6.9 if 6.7 = Yes; How long did your injury reduce your ability to work?<br>____________________________ |
| 6.10 Do you know of other producers who have been injured during charcoal production?<br>Yes / No | 6.11 *If 6.10 = Yes*; How did other charcoal producers get injured during charcoal production? | |

## 7. Techniques and knowledge

| | | |
|---|---|---|
| 7.1 How did you acquire your charcoal production skills? | 7.2 Where do you harvest wood for the charcoal you produce? | 7.3 How do you decide where to harvest the wood from? |
| 7.3 How do you decide, which wood/tree species to harvest for charcoal production? | | |
| 7.4 Do other charcoal producers use different sources of wood for charcoal production? (Which?, Why? / Why not?)<br>Yes / No | 7.5 Did you change your technique to improve the efficiency of charcoal production? (How?, Why? / Why not?)<br>Yes / No | 7.7 Do you consider any techniques to improve the quality of your charcoal? (Which, Why?)<br>Yes / No |
| 7.7 Do other producers in the village use a different technique? (Why / Why not?)<br>Yes / No | 7.8 What do you think about the techniques that other producers use? | 7.9 Does the village forest contain trees that can be used to produce quality charcoal? (Which?)<br>Yes / No |
| 7.10 Do you consider the species of a tree when you produce charcoal? (Why?)<br>Yes / No | 7.11 Do you take the state of the forest into consideration when you produce charcoal? (Why?)<br>Yes / No | 7.12 Do you know how to minimize the impact of charcoal production on the village forest? (How?)<br>Yes / No |

## 8. State of the forest & forest access

| | |
|---|---|
| 8.1 How far is the nearest forest from your house?<br>____________________________ | 8.2 Do you own or have rights to manage any forested land?<br>Yes / No |
| 8.2 *If 8.2 = yes*; How did you obtain the rights to manage the forested land (that you own)? | 8.3 *If 8.2 = yes*; What is the size of the forested land that you own or have the right to manage?<br>____________________________________________ |
| 8.3 *In your view*; Is there enough wood available to you in the village to continue producing charcoal over the next 10 to 20 years? (How can you tell?)<br>Yes / No | 8.4 *In your view*; Does the village forest regenerate fast enough for charcoal production to continue over the next 10 to 20 years? (How can you tell?)<br>Yes / No |
| 8.5 In your view; Did the amount of wood in the forest change over the past 5 years? (How, Why? / Why not?) | 8.6 *In your view*; Did the amount of trees that produce quality charcoal change over the past 5 years? (How, Why? / Why not?) |

<table>
<tr><td colspan="2">○ Decreased significantly<br>○ Decreased slightly<br>○ Increased slightly<br>○ Increased significantly<br>○ Unchanged</td><td colspan="2">○ Decreased significantly<br>○ Decreased slightly<br>○ Increased slightly<br>○ Increased significantly<br>○ Unchanged</td></tr>
<tr><td colspan="2">8.7 Do you know how much charcoal you are allowed to producer per year? (If yes; how much?)<br>Yes / No<br>____________________ kg</td><td colspan="2">8.8 Who decides the quantity of charcoal you are allowed to produce per year? (Why this institution?)<br>○ Do not know<br>○ Village council<br>○ District<br>○ NGO / Company</td></tr>
<tr><td colspan="2">8.9 Is everybody in the village allowed to produce the same quantity of charcoal?<br>Yes / No</td><td colspan="2">8.10 <i>If 8.9 = No</i>; Who is allowed to produce more charcoal and who is allowed to produce less charcoal? (Why?)<br>________________________<br>________________________<br>________________________</td></tr>
<tr><td colspan="2">8.11 <i>In your view</i>; Are the restrictions on the amount of charcoal that can be produced per person respected by all users? (Why? / Why not?)<br>Yes / No</td><td>8.12 What sanctions are in place to prevent that producers exceed the amount of charcoal that they are allowed to produce?</td><td>8.13 What sanctions are in place to prevent charcoal production without a permit?</td></tr>
</table>

## 9. Interactions with other charcoal producers

<table>
<tr><td>9.1 Do you work together with other charcoal producers? (Why? / Why not?)<br>Yes / No</td><td colspan="2">9.2 With whom of the charcoal producers do you prefer to work? (Why them?)<br>________________________________<br>________________________________<br>________________________________<br>________________________________<br>________________________________<br>________________________________</td></tr>
<tr><td>9.3 Are there other charcoal producers you work with?<br>Yes / No</td><td colspan="2">9.4 Who are the other charcoal producers you work with?<br>________________________________<br>________________________________<br>________________________________<br>________________________________<br>________________________________<br>________________________________</td></tr>
<tr><td>9.5 How many charcoal producers do you work with in total?</td><td>9.6 How many times do you generally see them per week?</td><td>9.7 Whom of these producers are your family or neighbors (indicate with F or N)?<br>________________________</td></tr>
</table>

| | | |
|---|---|---|
| ________________ producers | → **Indicate with a number in 7.2 and 7.4** | ____________________________________________<br>____________________________________________<br>____________________________________________ |

| | |
|---|---|
| 9.8 How did you meet the charcoal producers you work with? | 9.9 With whom of the charcoal producers do you exchange skills and knowledge about charcoal production?<br>________________________________________________________________________<br>________________________________________________________________________<br>________________________________________________________________________<br>________________________________________________________________________<br>________________________________________________________________________ |

| | |
|---|---|
| 9.10 With whom do you talk about the state of the forest and its species?<br>______________________________________________________________________<br>______________________________________________________________________<br>______________________________________________________________________<br>______________________________________________________________________ | 9.11 Which other topics do you talk about together? |

| |
|---|
| 9.12 Whom would you be willing to help out financially?<br>_______________________________________________________________________________________________<br>_______________________________________________________________________________________________ |

## 10. Interaction with other farmers

| | |
|---|---|
| 10.1 Do you work together with other farmers? (Why? / Why not?)<br>Yes / No | 10.2 *If 10.1 = Yes*; With whom of the farmers do you prefer to work? (Why them?)<br>________________________________________________________________________<br>________________________________________________________________________<br>________________________________________________________________________<br>________________________________________________________________________<br>________________________________________________________________________<br>________________________________________________________________________ |

| | |
|---|---|
| | ____________________________________________ |
| 10.3 How many times do you generally see them per week?<br>→ **Indicate with a number in 10.2** | 10.4 Whom of these farmers are your family or neighbors (indicate with F or N)?<br>____________________________________________<br>____________________________________________<br>____________________________________________<br>____________________________________________ |

| | |
|---|---|
| 10.5 With whom of the farmers do you exchange skills and knowledge about farming?<br>____________________________________________<br>____________________________________________<br>____________________________________________<br>____________________________________________ | 10.6 Which other topics do you talk about together? |

| | |
|---|---|
| 10.7 Who of the other farmers has helped you with farming? (In which way?)<br>____________________________<br>____________________________<br>____________________________<br>____________________________<br>____________________________ | 10.8 Who have you helped out with farming? (In which way?)<br>____________________________<br>____________________________<br>____________________________<br>____________________________<br>____________________________ |

## 11. Interaction with village council

| | |
|---|---|
| 11.1 Do you interact with members of the village council? (Why? / Why not?)<br>Yes / No | 11.2 *If 11.1 = Yes*; Whom from the village council do you interact with?<br>________________________________________<br>________________________________________<br>________________________________________<br>________________________________________<br>________________________________________ |

| | | | |
|---|---|---|---|
| 11.3 How many members of the village council do you interact with in total? | 11.4 How many times per month do you interact with these council members? | 11.5 Which topics do you talk about with members of the village council? | 11.6 Whom of the village council are your family or neighbors (indicate with F or N)?<br>_____________________ |

<table>
<tr><td>________________ members</td><td>→ <b>Indicate with a number in 11.2</b></td><td></td><td>______________________________<br>______________________________<br>______________________________</td></tr>
<tr><td colspan="3">11.7 Whom of the village council decides over charcoal production within the village forest?<br>______________________________________________<br>______________________________________________<br>______________________________________________</td><td>11.8 How many times per month do you interact with the members of the village council that decide over charcoal production within the forest?<br>→ <b>Indicate per person in 11.7</b></td></tr>
<tr><td>11.9 Would you get in contact with village council members if illegal charcoal production takes place in the village forest? (Why? / Why not?)<br>Yes / No</td><td colspan="3">11.10 <i>If 11.9 = Yes</i>; Who of the village council would you contact to notify them about illegal charcoal production in the village forest?<br>___________________________________________________________<br>___________________________________________________________<br>___________________________________________________________</td></tr>
<tr><td>11.11 Can you tell us how you would be able to obtain (more) land for farming or forestry?</td><td colspan="2">11.12 Who of the village council can allocate land for farming or forestry?<br>_________________________<br>_________________________<br>_________________________<br>_________________________</td><td>11.13 How regularly do you interact with the members of the village council that have the right to allocate land for farming or forestry?<br>→ <b>Indicate per person in 11.12</b></td></tr>
</table>

## 12. Interaction with TFCG

<table>
<tr><td>12.1 Do you interact with TFCG officials? (Why? / Why not?)<br>Yes / No</td><td colspan="2">12.2 Whom of TFCG do you interact with?<br>_________________________________________________________<br>_________________________________________________________<br>_________________________________________________________<br>_________________________________________________________<br>_________________________________________________________</td></tr>
<tr><td>12.3 How many TFCG officials do you interact with in total?<br>________________ members</td><td>12.4 How many times per month do you interact with these TFCG officials?<br>→ <b>Indicate with a number in 12.2</b></td><td>12.5 Which topics do you talk about with TFCG officials?</td></tr>
<tr><td colspan="2">12.6 Who of TFCG decides over charcoal production within the village forest?<br>______________________________________________<br>______________________________________________<br>______________________________________________</td><td>12.7 How regularly do you interact with the members of the TFCG that decide over charcoal production within the forest?<br>→ <b>Indicate in 12.6</b></td></tr>
<tr><td>12.8 Would you get in contact with TFCG officials for questions</td><td colspan="2">12.9 <i>If 12.8 = Yes</i>; Who of TFCG would you contact for more information about charcoal production?</td></tr>
</table>

| | |
|---|---|
| about charcoal production? (Why? / Why not?)<br>Yes / No | ____________________________________________<br>____________________________________________<br>____________________________________________ |
| 12.10 Would you get in contact with TFCG officials if illegal charcoal production takes place in the village forest? (Why? / Why not?)<br>Yes / No | 12.11 *If 12.10 = Yes*; Who of TFCG would you contact to notify them about illegal charcoal production in the village forest?<br>____________________________________________<br>____________________________________________<br>____________________________________________ |

## 13. Interaction with the Kilosa District Government

| | | |
|---|---|---|
| 13.1 Do you interact with members of district government? (Why? / Why not?)<br>Yes / No | 13.2 Whom from the district government do you interact with?<br>____________________________________________<br>____________________________________________<br>____________________________________________<br>____________________________________________<br>____________________________________________ | |
| 13.3 How many members of the district government do you interact with in total?<br>_____________ members | 13.4 How many times per year do you interact with these district government members?<br>→ **Indicate with a number in 13.2** | 13.5 Which topics do you talk with them about? |
| 13.6 Would you get in contact with district officials to acquire information about rules and regulations for charcoal production? (Why? / Why not?)<br>Yes / No | 13.7 *If 13.6 = Yes*; Which district official(s) would you contact to acquire information about rules and regulations for charcoal production?<br>____________________________________________<br>____________________________________________<br>____________________________________________ | |
| 13.8 Would you get in contact with district officials if illegal charcoal production takes place in the village forest? (Why? / Why not?)<br>Yes / No | 13.9 *If 13.8 = Yes*; Which district official(s) would you contact to notify them about illegal charcoal production in the village forest?<br>____________________________________________<br>____________________________________________<br>____________________________________________ | |

## 14. Interaction with Tanzania Forest Service

| | |
|---|---|
| 14.1 Do you interact with members of Tanzania Forest Service? (Why? / Why not?)<br>Yes / No | 14.2 Whom from Tanzania Forest Service do you interact with?<br>____________________________________________<br>____________________________________________<br>____________________________________________<br>____________________________________________ |

| | | |
|---|---|---|
| | ________________________________________________ | |
| 14.3 How many officials of the Tanzania Forest Service do you interact with in total?<br>____________ members | 14.4 How many times per year do you interact with these officials of Tanzania Forest Service?<br>→ **Indicate with a number in 14.2** | 14.5 Which topics do you talk with them about? |
| 14.6 Would you get in contact with officials of Tanzania Forest Service to acquire information about rules and regulations for charcoal production? (Why? / Why not?)<br>Yes / No | 14.7 *If 14.6 = Yes*; Which Tanzania Forest Service official(s) would you contact to acquire information about rules and regulations for charcoal production?<br>______________________________________________<br>______________________________________________<br>______________________________________________ | |
| 14.8 Would you get in contact with Tanzania Forest Service if illegal charcoal production takes place in the village forest? (Why? / Why not?)<br>Yes / No | 14.9 *If 14.8 = Yes*; Which Tanzania Forest Service officials would you contact to notify them about illegal charcoal production in the village forest?<br>______________________________________________<br>______________________________________________<br>______________________________________________ | |

## 15. Associations, life goals and support

| | | |
|---|---|---|
| 15.1 Are you a member of a charcoal producer association? (Why? / Why not?)<br>Yes / No | 15.2 *If 15.1 = Yes*; Which tasks do you have in the charcoal producer association? | 15.3 Do you take part in the decision making process of the charcoal producer association? (In what way?)<br>Yes / No |
| 15.4 Are you a member of another community association? (Why / Why not?)<br>Yes / No | 15.5 If 15.4 = Yes; Which community association is this and what are your tasks? | 15.6 Do you take part in the conventional decision making process within the village? (In what way?)<br>Yes / No |
| 15.7 How many associations are you a member of in total?<br>_____________ associations | 15.8 Do you feel like you have similar goals in life as other villagers (Why? / Why not?)<br>Yes / No | 15.9 Do you feel supported by other villagers (Why? / Why not?)<br>Yes / No |
| 15.10 Do you feel supported by the village committee (Why / Why not?)<br>Yes / No | 15.11 Do you feel supported by TFCG (Why? / Why not?)?<br>Yes / No | 15.12 Do you feel supported by the district government? (Why? / Why not?)<br>Yes / No |
| 15.13 Do you feel supported by the Tanzania Forest Service?<br>Yes / No | 15.14 *In your view*; How can the village committee and TFCG support increase their support to you in the future? | 15.15 *In your view*; How can the district government and Tanzania Forest Service increase their support to you in the future? |

## 16. Physical capital

| | | |
|---|---|---|
| 16.1 Do you own a house? | 16.2 How many houses do you own? | 16.3 How many new houses did you construct over your lifetime? |

|  |  |  |
|---|---|---|
| Yes / No | 1 / 2 / 3 / 4 / 5 / 6 | ____________________ houses |
| 16.4 What material are your walls made of?<br>○ Mud<br>○ Unburned bricks<br>○ Burned bricks<br>○ Cement bricks | 16.5 What material is your roof made of?<br>○ Grasses/palm leaves<br>○ Corrugated iron sheets<br>○ Tiles | 16.6 What material is your floor made of?<br>○ Sand / Dust<br>○ Cement / Tiles |
| 16.7 How many rooms does the house(s) you live in have?<br>____________________ rooms | 16.8 How many bicycles do you have?<br>__________________ bicycles | 16.9 Do you own a motorbike?<br>Yes / No |
| 16.10 *If 16.9 = Yes*; How many motorbikes do you own?<br>_________________ motorbikes | 16.11 Do you use your bike or motorbike to transport the charcoal you produce?<br>Yes / No | 16.12 Do you own a car?<br>Yes / No |
| 16.13 Is you house adjacent to a road?<br>Yes / No | 16.14 *If 16.13 = Yes*; Is the road adjacent to your house a main road?<br>Yes / No | 16.15 *If 16.13 = Yes*; Is the road adjacent to your house made of asphalt or other hard materials?<br>Yes / No |
| 16.16 *If 16.13 = Yes*; Is the road adjacent to your house being maintained by the village, district or national government?<br>Yes / No | 16.17 Do you have access to drainage in your house?<br>Yes / No | 16.18 Do you have a toilet in your house?<br>Yes / No |
| 16.19 *In your view*; Did the amount of possessions you have change over the past 5 years?<br>○ Decreased significantly<br>○ Decreased slightly<br>○ Increased slightly<br>○ Increased significantly<br>○ Unchanged | 16.20 *In your view*; Did the quality of the road adjacent / near your house change over the past 5 years?<br>○ Decreased significantly<br>○ Decreased slightly<br>○ Increased slightly<br>○ Increased significantly<br>○ Unchanged | 16.21 *In your view*; Did the condition of your house change over the past 5 years?<br>○ Decreased significantly<br>○ Decreased slightly<br>○ Increased slightly<br>○ Increased significantly<br>○ Unchanged |

## 17. Notes (Indicate the topic of the note and write down keywords)

Notes 1:

________________________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

________________________________________________________________

Notes 2:

Notes 3:

## Consent form used in this study:

### Social capital of charcoal producers and its impact on other livelihood capitals

*Responsible for research project*: Maria J. Santos, Hanneke van 't Veen
*Institution*: Winterthurerstrasse 190, 8057 Zürich, Switzerland
*Contact Information*: Maria J. Santos, Department of Geography Y25-J-68, Winterthurerstrasse 190, 8057 Zürich, Switzerland

### Information on the research project

Charcoal producers have different livelihood resources they depend upon, such as (i) the income they derive from charcoal production (i.e. financial capital), (ii) the woody biomass resources they depend upon for production (i.e. natural capital), (iii) their skills and knowledge of charcoal production (i.e. human capital), (iv) their access to housing and infrastructure (i.e. physical capital), and finally (v) their social networks (i.e. social capital) (FAO 2017). In this study we are interested in how the social networks and interactions of charcoal producers influence the amount of charcoal they produce, their income, their knowledge and charcoal producer skills and also their overall assets. This will provide an insight in the importance of social networks and interactions of charcoal producers in pursuing their livelihoods. By comparing the livelihood resources of charcoal producers between villages that are involved in the TFCG project on community charcoal production and villages that are not involved in this project, we will gain a better understanding of the impact of these types of projects on the lives of charcoal producers. By including information about the formal and informal governance of charcoal production by institutions, including the village councils, TFCG, the district of Kilosa and Tanzania Forest Services, we gain a better understanding of the influence of these institutions on charcoal producer livelihoods and charcoal production in general. This data gathered during this project can be used to improve policies on charcoal production in Tanzania and around the world.

This PhD project for which the data will be acquired is funded by the University Research Priority Program of Global Change and Biodiversity (URPP-GCB) of the University of Zurich in Switzerland.

### Taking part in the study

Your participation in this research project consists of an interview that lasts about two hours and will be audio-recorded. The interviewers will also note down some of your answers to the questions on a survey sheet. You will be asked questions on the topic of your livelihoods, including questions about i) charcoal production, ii) the income you derive from charcoal production, iii) farming, iv) trees on your land, v) the forest, vi) your interactions with other charcoal producers and members of the village council, and v) the access you have to housing and infrastructure.

### Withdrawal from the participation or the consent

The participation in this research project is voluntary. You have at all times the right to withdraw from participating in the research project, without having to state the reason. You also have the right to withdraw your consent which will result in your personal information being removed so that it cannot be linked to you anymore.

### Data protection, confidentiality and future use

The data collected in the research project *Social capital of charcoal producers and its impact on other livelihood capitals* will only be used for strictly scientific research purposes. Your name or other identifying information will not be revealed in any publication or handed to third parties, and will be kept confidential.

Your contribution (the audio-recorded interviews and hand-written survey sheets) will be stored for long-term preservation in the secure environment of the national data archive of FORS, Swiss Centre of Expertise in the Social Sciences, funded by the State Secretariat for Education, Research, and Innovation. Your information will be de-identified.

Your de-identified information may be made available to accredited researchers and students affiliated with an institution of higher learning for secondary research with prior agreement from the primary research team, only after they have signed a data protection contract obliging them to refrain from trying to identify persons and requiring them to use the data in a way that respects your confidentiality and within the framework of existing data protection legislation.

**Consent**

I have read and understood the information in this form, or it has been read to me. I have been able to ask questions about the research project *Social capital of charcoal producers and its impact on other livelihood capitals* and these have been answered to my satisfaction.

I consent freely to participating in the research project and I give permission for my contribution to be stored in a secure environment and to be made available in de-identified form for future research and learning.

**Signatures**

Name of participant Signature Date

Name of researcher Signature Date

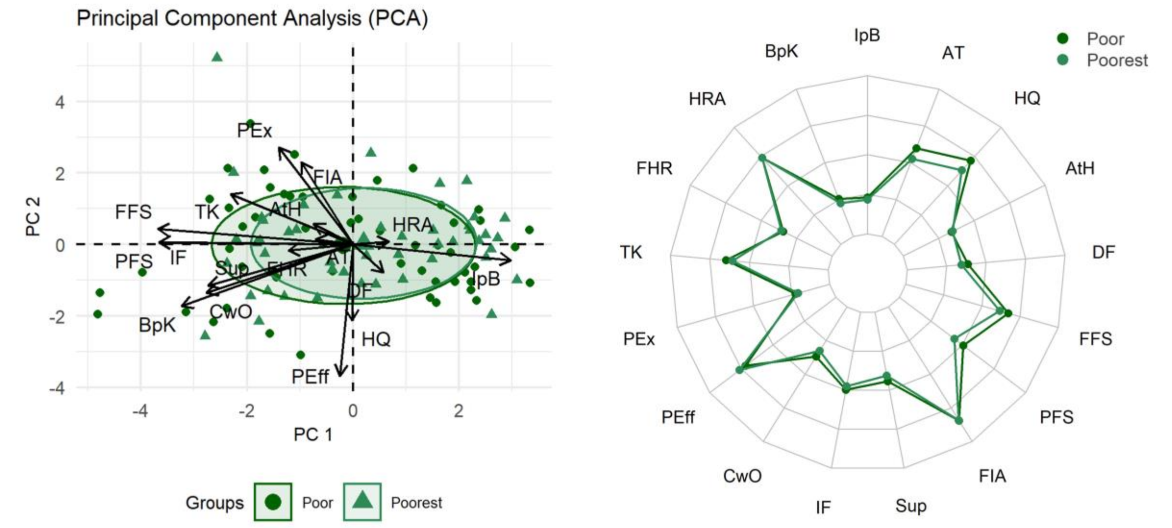
**The participant has received a signed copy of the informed consent form.**

# Figures and tables:

**Table A1.** The number of charcoal producers per village included per livelihood capital indicator for the comparative analysis of livelihood capital access across governance regimes (Kruskal-Wallis test), and the correlation analyses through Spearman correlation matrices and PCAs. The number of charcoal producers included differ between livelihood capital indicators for the comparative analysis because of different sample sizes per village (see Table 2) and because charcoal producers did not always provide an answer to the questions included in livelihood capital indicators. The number of charcoal producers included in the comparative analysis differs from those included in the correlation analyses because Spearman correlations and PCAs require that data for all indicators included in the analyses is available. Therefore, we only included the charcoal producers for which we could derive an estimation for all livelihood indicators included in the correlation analyses. Because many charcoal producers could not estimate the number of kilns they create per year, we had limited data for the charcoal income (CI) indicator. Hence, we decided to remove this indicator from the correlation analyses to increase the sample size.

| | **Comparative analysis** | | | | | | **Correlation analyses** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** | **OA3** | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** | **OA3** |
| Income per bag (IpB) | 37 | 26 | 27 | 27 | 15 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Charcoal bags per kiln (BpK) | 34 | 26 | 28 | 27 | 16 | 24 | 31 | 20 | 14 | 18 | 12 | 12 |
| Charcoal production (CP) | 36 | 24 | 21 | 17 | 15 | 20 | Not included | | | | | |
| Charcoal income (CI) | 33 | 24 | 21 | 16 | 14 | 25 | Not included | | | | | |
| Health risk awareness (HRA) | 37 | 26 | 26 | 28 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Faced health risks (FHR) | 37 | 26 | 26 | 28 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Technical knowledge (TK) | 37 | 26 | 28 | 28 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Production experience (PEx) | 37 | 25 | 27 | 27 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Production efficiency (PEff) | 34 | 25 | 24 | 26 | 16 | 19 | 31 | 20 | 14 | 18 | 12 | 12 |
| Cooperation with others (CwO) | 37 | 26 | 28 | 28 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Interaction formality (IF) | 37 | 26 | 27 | 28 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Support (Sup) | 37 | 26 | 27 | 28 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Forest impact awareness (FIA) | 36 | 26 | 24 | 25 | 16 | 24 | 31 | 20 | 14 | 18 | 12 | 12 |
| Past forest sustainability (PFS) | 37 | 24 | 23 | 28 | 16 | 21 | 31 | 20 | 14 | 18 | 12 | 12 |
| Future forest sustainability (FFS) | 36 | 25 | 24 | 22 | 16 | 22 | 31 | 20 | 14 | 18 | 12 | 12 |
| Distance from forest (DF) | 37 | 26 | 27 | 27 | 13 | 21 | 31 | 20 | 14 | 18 | 12 | 12 |
| Access to housing (AtH) | 37 | 24 | 23 | 28 | 16 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Housing quality (HQ) | 37 | 26 | 27 | 27 | 15 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |
| Access to tools (AT) | 36 | 26 | 26 | 28 | 15 | 25 | 31 | 20 | 14 | 18 | 12 | 12 |

**Separation by wealth category**



**Separation by gender**

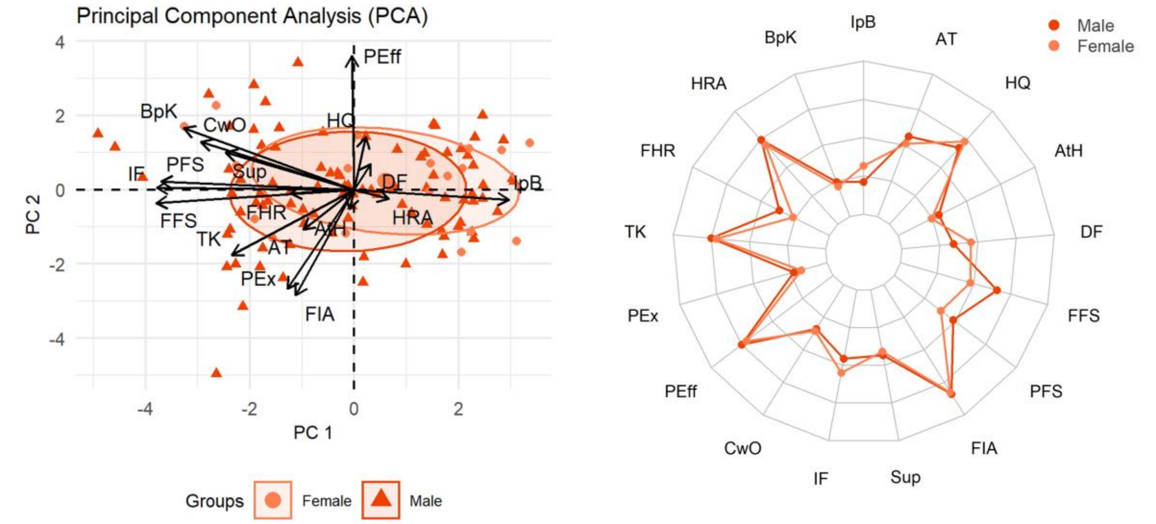


**Figure A1.** Radar charts and PCAs showing the average access charcoal producers have to different livelihood capital indicators per wealth category (top panel) and per gender (bottom panel) and their interactions. CB-villages are those under community-based natural resources management (CBNRM), while OA-villages are under open access. An explanation of each livelihood capital indicator and a rationale for their inclusion can be found in Table 3. The livelihood indicators have been normalized to range between 0.1 and 1, using the transformation of Kearney et al. (2017).

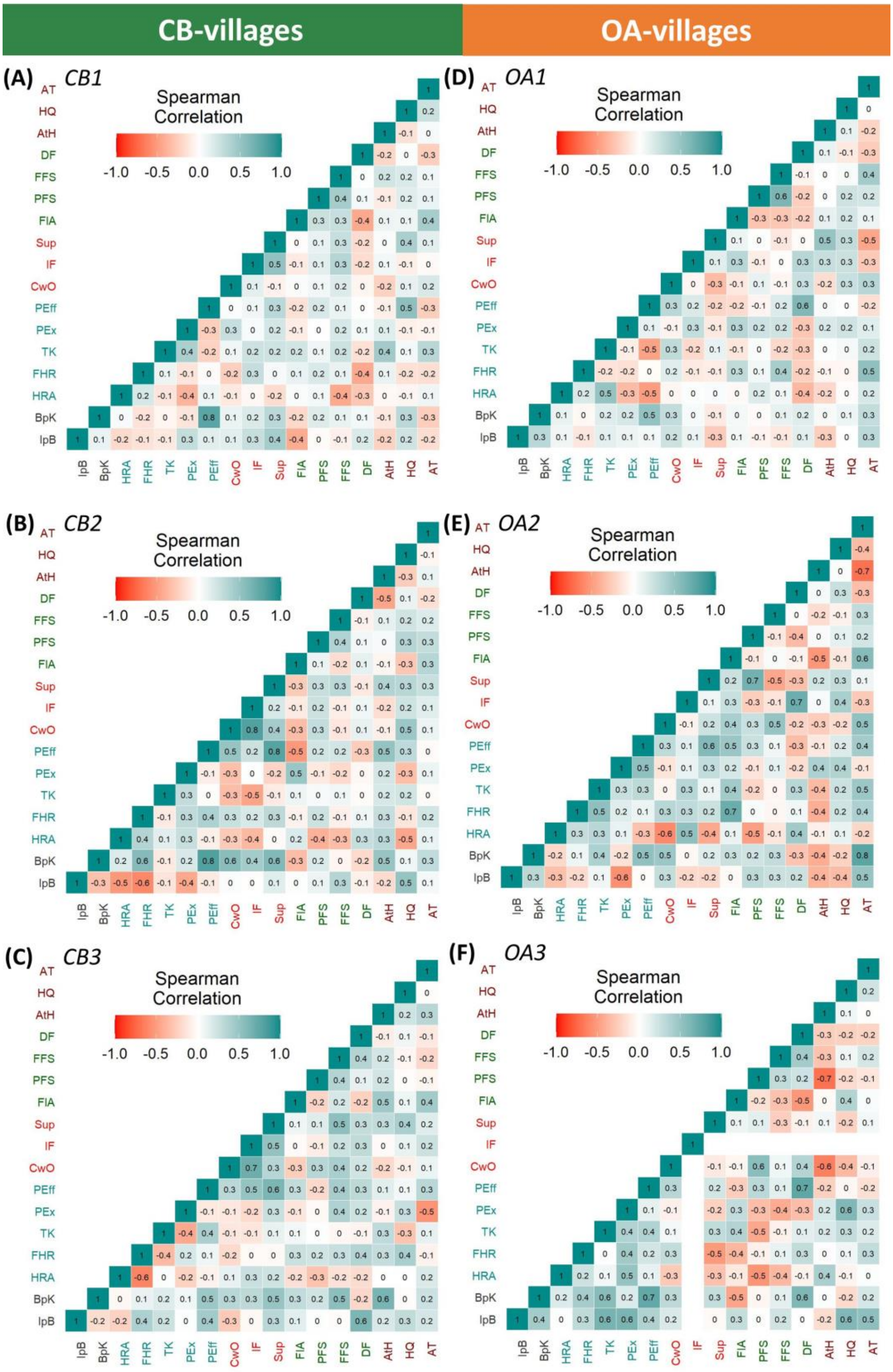


**Figure A2.** Spearman correlation matrices showing correlations between livelihood capital indicators per village. CB-villages are those under community-based natural resources management (CBNRM), while OA-villages are under open access. An explanation of each livelihood capital indicator and a rationale for their inclusion can be found in Table 3, which

**Table A2.** Overview of the p-values derived from the Kruskal-Wallis tests for the charcoal production (CP) indicator. P-values lower than 0.05 indicate significant differences between villages. CB-villages are those under community-based natural resources management (CBNRM), while OA-villages are under open access. An explanation of the livelihood capital indicator and a rationale for its inclusion can be found in Table 3, which follows the same color-code scheme.

**Charcoal production (CP)**

| | **CB1** | **CB2** | **CB3** | **OA1** | **OA2** |
|---|---|---|---|---|---|
| **CB2** | 0.039 | | | | |
| **CB3** | 0.074 | 0.964 | | | |
| **OA1** | 0.055 | 0.002 | 0.013 | | |
| **OA2** | 0.076 | 0.002 | 0.012 | 0.637 | |
| **OA3** | 0.164 | 0.006 | 0.016 | 0.669 | 0.987 |

**Table A3.** Overview of the p-values derived from the Kruskal-Wallis tests per livelihood capital indicator. P-values lower than 0.05 indicate significant differences between villages. CB-villages are those under community-based natural resources management (CBNRM), while OA-villages are under open access. An explanation of each livelihood capital indicator and a rationale for their inclusion can be found in Table 3, which follows the same color-code scheme.

**Income per bag (IpB)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.005 | | | | |
| CB3 | 0.196 | 0.024 | | | |
| OA1 | 0.000 | 0.000 | 0.000 | | |
| OA2 | 0.000 | 0.000 | 0.000 | 0.069 | |
| OA3 | 0.000 | 0.000 | 0.000 | 0.000 | 0.117 |

**Charcoal bags per kiln (BpK)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.615 | | | | |
| CB3 | 0.825 | 0.408 | | | |
| OA1 | 0.000 | 0.000 | 0.000 | | |
| OA2 | 0.000 | 0.000 | 0.006 | 0.064 | |
| OA3 | 0.000 | 0.000 | 0.002 | 0.397 | 0.578 |

**Charcoal income (CI)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.033 | | | | |
| CB3 | 0.213 | 0.633 | | | |
| OA1 | 0.096 | 0.562 | 0.939 | | |
| OA2 | 0.726 | 0.198 | 0.533 | 0.318 | |
| OA3 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

**Health risk awareness (HRA)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.976 | | | | |
| CB3 | 0.464 | 0.372 | | | |
| OA1 | 0.716 | 0.733 | 0.205 | | |
| OA2 | 0.703 | 0.584 | 0.723 | 0.391 | |
| OA3 | 0.655 | 0.688 | 0.207 | 0.947 | 0.392 |

**Faced health risk (FHR)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.479 | | | | |
| CB3 | 0.681 | 0.377 | | | |
| OA1 | 0.507 | 0.865 | 0.415 | | |
| OA2 | 0.844 | 0.668 | 0.635 | 0.734 | |
| OA3 | 0.396 | 0.930 | 0.264 | 0.941 | 0.554 |

**Technical knowledge (TK)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.006 | | | | |
| CB3 | 0.174 | 0.001 | | | |
| OA1 | 0.017 | 0.000 | 0.469 | | |
| OA2 | 0.045 | 0.000 | 0.469 | 0.831 | |
| OA3 | 0.005 | 0.000 | 0.182 | 0.387 | 0.620 |

**Production experience (PEx)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.511 | | | | |
| CB3 | 0.158 | 0.120 | | | |
| OA1 | 0.011 | 0.020 | 0.360 | | |
| OA2 | 0.791 | 0.697 | 0.363 | 0.068 | |
| OA3 | 0.140 | 0.058 | 0.726 | 0.692 | 0.179 |

**Production efficiency (PEff)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.505 | | | | |
| CB3 | 0.000 | 0.000 | | | |
| OA1 | 0.870 | 0.412 | 0.000 | | |
| OA2 | 0.731 | 0.779 | 0.000 | 0.727 | |
| OA3 | 0.004 | 0.001 | 0.003 | 0.002 | 0.002 |

**Cooperation with others (CwO)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.152 | | | | |
| CB3 | 0.968 | 0.325 | | | |
| OA1 | 0.002 | 0.000 | 0.029 | | |
| OA2 | 0.002 | 0.000 | 0.011 | 0.286 | |
| OA3 | 0.000 | 0.000 | 0.002 | 0.127 | 0.931 |

**Interaction formality (IF)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.336 | | | | |
| CB3 | 0.089 | 0.009 | | | |
| OA1 | 0.000 | 0.000 | 0.001 | | |
| OA2 | 0.000 | 0.000 | 0.000 | 0.008 | |
| OA3 | 0.000 | 0.000 | 0.000 | 0.000 | 0.640 |

**Support (Sup)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.188 | | | | |
| CB3 | 0.158 | 0.023 | | | |
| OA1 | 0.021 | 0.003 | 0.421 | | |
| OA2 | 0.443 | 0.079 | 0.682 | 0.293 | |
| OA3 | 0.053 | 0.005 | 0.663 | 0.728 | 0.416 |

**Forest impact awareness (FIA)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.075 | | | | |
| CB3 | 0.075 | 0.001 | | | |
| OA1 | 0.447 | 0.019 | 0.351 | | |
| OA2 | 0.227 | 0.013 | 0.902 | 0.562 | |
| OA3 | 0.001 | 0.000 | 0.132 | 0.021 | 0.226 |

**Past forest sustainability (PFS)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.023 | | | | |
| CB3 | 0.162 | 0.006 | | | |
| OA1 | 0.000 | 0.000 | 0.000 | | |
| OA2 | 0.000 | 0.000 | 0.000 | 0.934 | |
| OA3 | 0.000 | 0.000 | 0.049 | 0.062 | 0.045 |

**Future forest sustainability (FFS)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.675 | | | | |
| CB3 | 0.082 | 0.056 | | | |
| OA1 | 0.000 | 0.000 | 0.001 | | |
| OA2 | 0.000 | 0.000 | 0.030 | 0.301 | |
| OA3 | 0.000 | 0.000 | 0.000 | 0.497 | 0.100 |

**Distance from forest (DF)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|
| CB2 | 0.056 | | | | |
| CB3 | 0.794 | 0.042 | | | |
| OA1 | 0.000 | 0.140 | 0.000 | | |
| OA2 | 0.858 | 0.178 | 0.953 | 0.008 | |
| OA3 | 0.954 | 0.053 | 0.983 | 0.001 | 0.985 |

**Access to housing (AtH)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|

**Housing quality (HQ)**

| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|

**Access to tools (AT)**

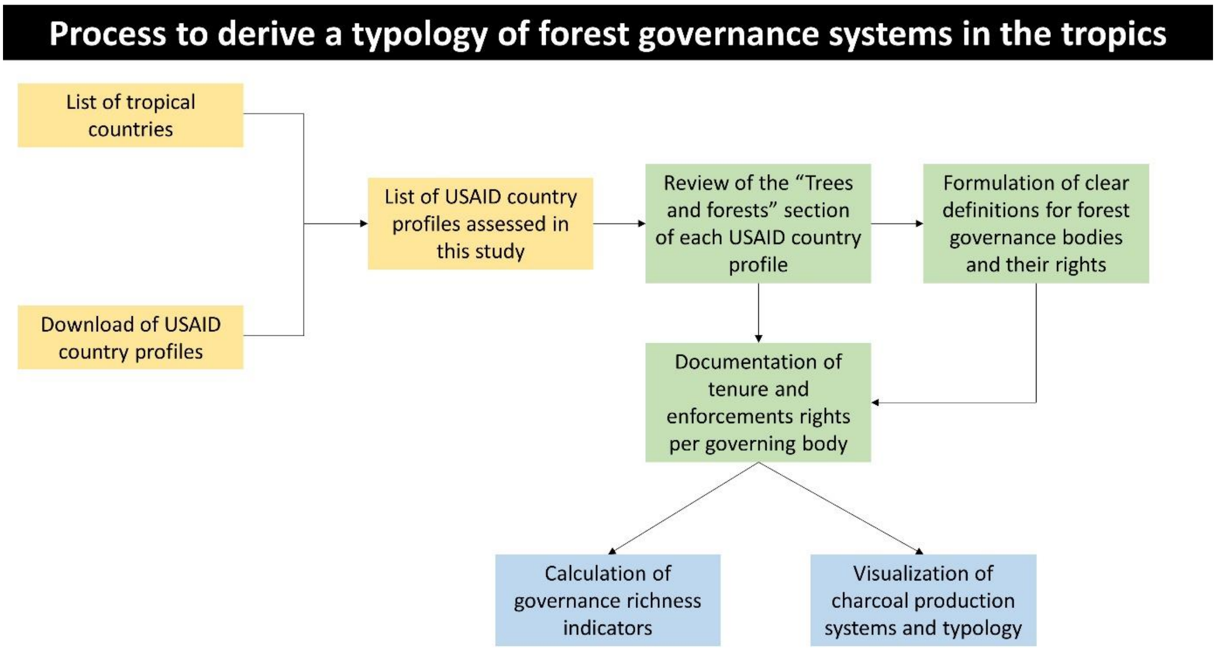
| | CB1 | CB2 | CB3 | OA1 | OA2 |
|---|---|---|---|---|---|

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **CB2** | 0.219 | | | | | **CB2** | 0.005 | | | | | **CB2** | 0.056 | | | | |
| **CB3** | 0.615 | 0.604 | | | | **CB3** | 0.196 | 0.024 | | | | **CB3** | 0.086 | 0.902 | | | |
| **OA1** | 0.013 | 0.520 | 0.172 | | | **OA1** | 0.000 | 0.000 | 0.000 | | | **OA1** | 0.372 | 0.255 | 0.332 | | |
| **OA2** | 0.375 | 0.124 | 0.290 | 0.009 | | **OA2** | 0.000 | 0.000 | 0.000 | 0.069 | | **OA2** | 0.871 | 0.163 | 0.210 | 0.613 | |
| **OA3** | 0.536 | 0.109 | 0.304 | 0.007 | 0.882 | **OA3** | 0.000 | 0.000 | 0.000 | 0.000 | 0.117 | **OA3** | 0.806 | 0.105 | 0.156 | 0.515 | 0.988 |

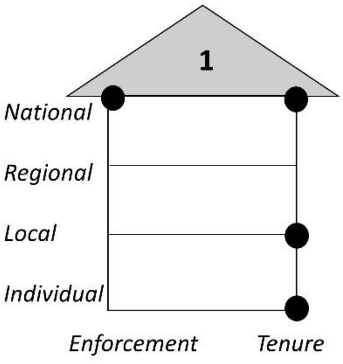
# Appendix Chapter 8

### Supplementary Materials A

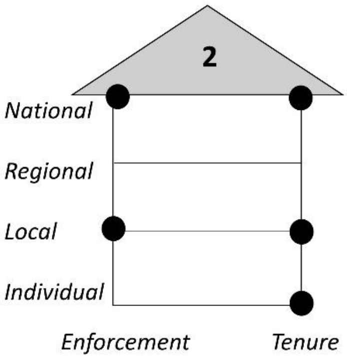
An overview of the steps that were taken in the screening and content analysis of the 54 USAID Country Profiles to derive a typology of forest governance systems of tropical countries.



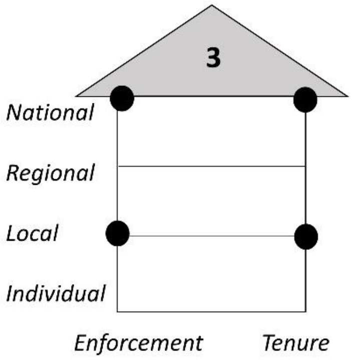
A typology of forest governance systems in tropical countries around the world based on the governance rights they have in the forest governance system (i.e. enforcement and/or tenure) and the types of governing bodies they assign these roles to (i.e. governing bodies operating on national, regional, local and/or individual scale). Enforcement is defined as the formal right to enforce (by-) laws on forest use and protection. Tenure is the formal right to tend forest land or trees, such as ownership and lease rights.  The typology was informed by the UAID country profiles because they provide a detailed and consistent overview of forest governance in tropical countries around the world ("USAID LANDLINKS - Country Profiles," 2020). Governance information from other sources is scattered and provided in different languages, which makes it challenging to utilize.



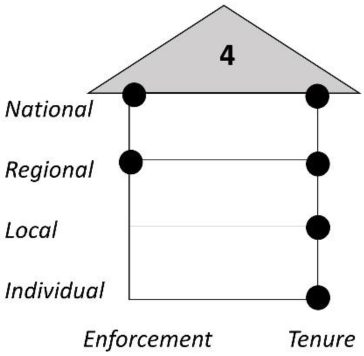
**Country**:
1. Burkina Faso
2. Burundi
3. Cambodia
4. Cameroon
5. Chad
6. El Salvador
7. Honduras
8. Ivory Coast
9. Laos
10. Liberia
11. Mozambique
12. Paraguay
13. Panama
14. Peru
15. Philippines
16. Sierra Leone
17. Thailand



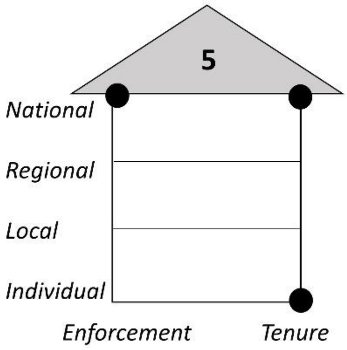
**Country**:
1. Central African Republic
2. Ghana
3. Guatemala
4. Haiti
5. Mexico
6. Namibia
7. Nicaragua



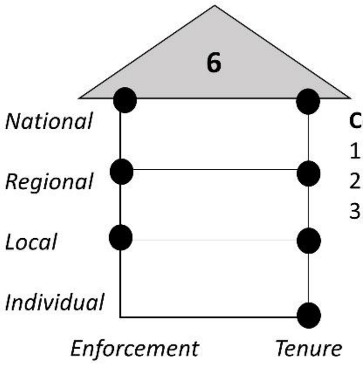
**Country**:
1. Botswana
2. Democratic Republic of Congo
3. Guinea
4. Madagascar
5. Niger
6. Senegal



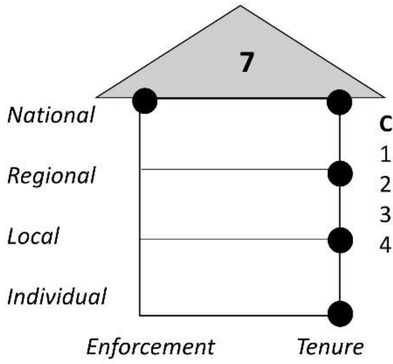
**Country**:
1. India
2. Indonesia
3. Uganda
4. Zimbabwe



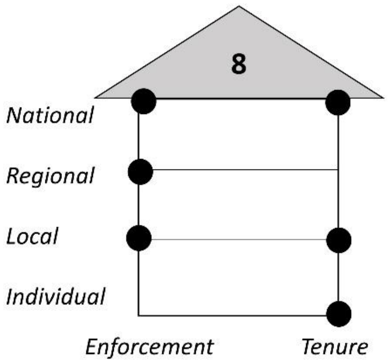
**Country**:
1. Angola
2. Congo
3. Dominican Republic
4. Jamaica



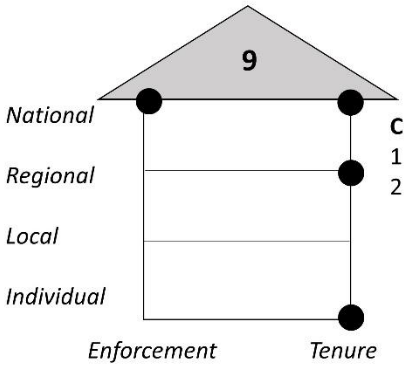
**Country**:
1. Brazil
2. Ecuador
3. Tanzania



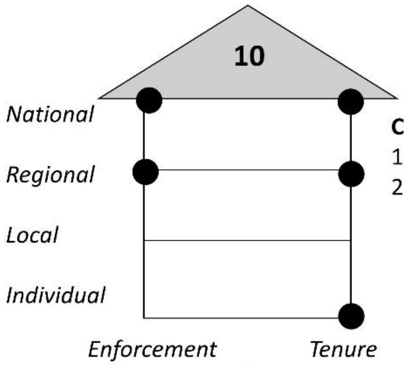
**Country**:
1. Bangladesh
2. Ethiopia
3. South Sudan
4. Sudan



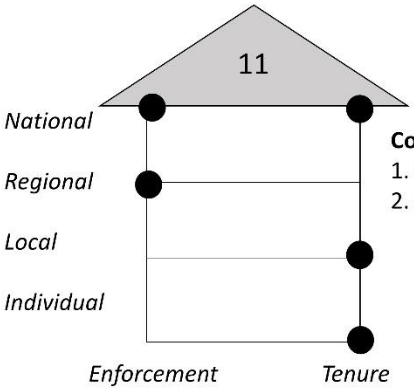
**Country**:
1. Malawi
2. Mali



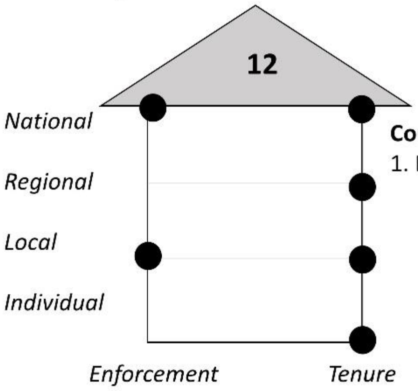
**Country**:
1. Costa Rica
2. Panama



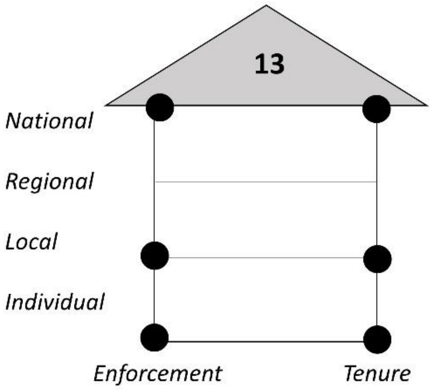
**Country**:
1. Nigeria
2. Rwanda



**Country**:
1. Vietnam
2. Zambia



**Country**:
1. Bolivia



**Country**:
1. Kenya

**Table A.1.** An overview of the USAID Country Profile information from which the role division of national, regional, local and individual governing bodies is determined for the right of Tenure. Tenure is the formal right to tend forest land or trees, such as ownership and lease rights. Governing bodies can take on multiple roles at once or may not have a specific role in forest governance. National governing bodies include ministries but also autonomous government agencies that operate at a national scale. Regional governing bodies operate at a regional level, such as a district or a State. Local governing bodies operate at municipality or village level and may include village or municipality governments and committees, but also NGOs. Finally, individual governing bodies include individual people and companies that operate at a local scale on the forest land or trees that they own, lease or obtain user rights over. The USAID Country Profiles can be found on the following website: https://www.land-links.org/country-profiles/. Information from USAID Country Profiles is only provided about the governing bodies that were found to have the tenure rights. The text are direct quotes from the original text found in the USAID Country Profiles.

## Right of tenure

| | **National** | **Regional** | **Local** | **Individual** | **Unspecified** |
|---|---|---|---|---|---|
| **Angola** | "After gaining independence, the country's constitution stated that all lands and forests in Angola belong to the state except the plantations which are under private companies (see Table 5) " | | | "After gaining independence, the country's constitution stated that all lands and forests in Angola belong to the state except the plantations which are under private companies (see Table 5) " | |
| **Bangladesh** | " All major forests are owned or controlled by the government (FAO)." "Under the Bangladesh Private Forest Act 1959, the government can take over management of privately-owned forest land, land that could become forested, or land that has lain fallow for more than three years. The law allows the government to require private forest-land owners to develop and abide by forest management plans or risk loss of the forest land to the state (FAO 2000)." | "All major forests are owned or controlled by the government (FAO). The Revenue Department of the government owns the unclassed state forests (USF, over 0.73 million ha) but most is under the control of district administrations." | "There has been some formal or near- formal recognition of customary resource rights (such as timber rights in areas of prior timber use by local communities) but such recognition has generally not been implemented in practice. In some instances, customary rights to resources have been formalized and recognized in practice, such as indigenous people's rights to minor forest produce (e.g., seeds, honey)." | "Under the Bangladesh Private Forest Act 1959, the government can take over management of privately-owned forest land, land that could become forested, or land that has lain fallow for more than three years." "The law allows the government to require private forest-land owners to develop and abide by forest management plans or risk loss of the forest land to the state (FAO 2000).""The ban also led to development of private-sector timber production, which now produces over 80% of the locally harvested timber marketed in Bangladesh." | |

| | | | | | |
|---|---|---|---|---|---|
| **Bolivia** | "Under the 2009 Constitution and the Forest Act of 1996, the government owns Bolivia's state forests and nationally protected areas." | "The IBAMA enforces compliance with the Forest Code through its regional offices in each state, with the support of armed forest police battalions in case of violent confrontations with illegal loggers. The CONAMA is the policy-development and consulting arm of the MMA, with strong representation from civil society, including nongovernmental organizations (NGOs) (Tomaselli and Sarre 2005; Rylands and Brandon 2005)." | "TCO concessions correspond to the traditional areas owned by indigenous people. Under customary law, forests in Bolivia belong to the community. The community closest to the forestland is entitled to use the forest products, including firewood, fruit, and medicinal plants (Lastarria-Cornhiel et al. 2008). Forestland can be vested in, or concessions can be allotted to: (1) private individuals, entities and companies; (2) communal groups such as families, indigenous groups through TCOs or organized migrant colonists; and (3) the government (ARD 2002)." "Local residents can access forests and forest products through a community forest management model implemented by local forest cooperatives. Forest cooperatives and lowland indigenous communities can receive access to forest reserves. The government grants Local Social Association (Agrupación Social del Lugar, or ASL) concessions in municipal forest areas to groups of 20 or more rural people who have proved that they previously had been using the forest resources." | "Owners of private forests have the right to exploit the forest resources on their land, subject to the requirement of a forest management plan." | |
| **Botswana** | "Thirty-one percent of the country's total land area is designated as nationally-protected areas." "Botswana's Forest Act authorizes the government to grant concessions for timber harvesting in forest reserves. However, the government has periodically closed the reserves to harvesting in an effort to prevent unsustainable use of forest resources (FAO 2003; USAID 2008; FAO 2008c)." | | "The vast majority of Botswana's woodlands and forests are on tribal land and are considered open-access resources. Access to and use of forest resources is subject to the Tribal Land Act, which is consistent with customary law (Adams et al. 2003; ROB 2002)." | | |

| | | | | | |
|---|---|---|---|---|---|
| **Brazil** | "0.20 million square kilometers of government-owned APPs." "States and municipalities license activities with impacts restricted to their territories. In practice, there is a struggle among municipal, state, and national environment organizations over the licensing of large-scale activities, and activities that generate more resources for environmental agencies are often a reason for disputes." | "States and municipalities license activities with impacts restricted to their territories. In practice, there is a struggle among municipal, state, and national environment organizations over the licensing of large-scale activities, and activities that generate more resources for environmental agencies are often a reason for disputes." | "1.03 million square kilometers of indigenous lands." "Local communities have been accorded commercial forest rights under several pieces of legislation. In addition, the 2004 Presidential Decree based on Law No. 9,985 grants local people long-term use rights to extractive reserves on federal and state lands. The PNF allows communities varying degrees of commercial forest rights, including rights to extractive reserves on forests on new agricultural settlement areas (Rylands and Brandon 2005; Toni 2006; Larson et. al. 2008)." | "It aims to bring 0.50 million square kilometers of national forests under sustainable management by 2010 and establish 0.20 million square kilometers of forest plantations on private lands." | |
| **Burkina Faso** | "Public forests are distributed between the holdings of the State and the holdings of the decentralized local communities." "The State, as well as local collectives, can delegate the management of forest resources to third parties, based on a management plan and a contract of concession with terms of reference." | | "Public forests are distributed between the holdings of the State and the holdings of the decentralized local communities." "The State, as well as local collectives, can delegate the management of forest resources to third parties, based on a management plan and a contract of concession with terms of reference." | "In Burkina Faso, the forest domain is comprised of public forests and private forests (as defined by article 9 of the new draft Forest Code). Private ownership of forests is permitted, by either people or corporations who have legally acquired forested areas or planted the trees." "Private holders of property rights to forests are required to hold a legally valid title." | |
| **Burundi** | "Under formal law, forestland and forest resources are owned by the state, communes (local authorities), or private individuals." "The Forest Code governs all forests, regardless of ownership, and sets various restrictions on forest use. The Forest Code bans clearing in state forests and afforested areas and sets rules for clearing on communal and private forestland." | | "Under formal law, forestland and forest resources are owned by the state, communes (local authorities), or private individuals." "The Forest Code bans clearing in state forests and afforested areas and sets rules for clearing on communal and private forestland." | "Under formal law, forestland and forest resources are owned by the state, communes (local authorities), or private individuals." "The Forest Code bans clearing in state forests and afforested areas and sets rules for clearing on communal and private forestland." | |

| | | | | | |
|---|---|---|---|---|---|
| **Cambodia** | "Under the Forestry Law, usufruct rights to forest resources can be conveyed by the state to designated beneficiaries by means of forest concessions (limited usufruct rights) and community forest designations (limited usufruct rights)." | | "Although current forest law and forest management practices by the State do not recognize customary tenure with relation to forests, The state recognizes traditional user rights of local communities living near forest reserves. A Community Forest can be initiated and established by local communities or the Forestry Administration. In order to establish a Community Forest, the local community must submit a written request to the Forestry Administration." | "As of 2001 30 companies had received forest concessions covering and estimated 6.3 million hectares (Beang and Sethaphal 2004; GTZ 2009; Sophal et al. 2001)." | |
| **Cameroon** | "The Forest Law recognizes three types of forests: (1) state forests (e.g., nature reserves, national parks, reforestation areas, forest plantations, buffer zones); (2) collective, private and council forests, to which citizens have harvest rights, but whose uses are restricted; and (3) national domain forests, which includes all other forestland (GOC Forest Law 1994)." "The state is responsible for the protection of the country's forests and sets a standard of maintaining at least 30% of total land area as protected, permanent forest." | | "The Forest Law recognizes three types of forests: (1) state forests (e.g., nature reserves, national parks, reforestation areas, forest plantations, buffer zones); (2) collective, private and council forests, to which citizens have harvest rights, but whose uses are restricted; and (3) national domain forests, which includes all other forestland (GOC Forest Law 1994)." "Communities with customary rights to forestland can organize as a legal entity and apply to register up to 5000 hectares as a community forest. To establish a community forest, communities must map the boundaries and inventory the forest resources." | ""The Forest Law recognizes three types of forests: (1) state forests (e.g., nature reserves, national parks, reforestation areas, forest plantations, buffer zones); (2) collective, private and council forests, to which citizens have harvest rights, but whose uses are restricted; and (3) national domain forests, which includes all other forestland (GOC Forest Law 1994)." Private landowners with forests are required to submit a management plan to the forest department that indicates how forest resources will be managed sustainably (GOC Forest Law 1994; Cerruti et al. 2008)." | |
| **Central African Republic** | "The current CAR Forest Code (Code Forestier de la République Centrafricaine) was adopted in October 2008. The Forest Code provides for state ownership of the country's forests and divides the forests into the permanent forest domain and non-permanent forest domain." "The majority of the country's forestland is state forest domain, including production forests, forest reserves, game parks, and forests that | | "The Forest Code recognizes customary rights to forest resources, granting local communities use-rights to forest land and forest products. All use-rights recognized by the formal law are subject to state definition and control (ARD 2007a)." | "Individuals and entities developing non-permanent forests can obtain rights to forest resources, consistent with government regulations (ARD 2007a)." | |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
|  | are subject to industrial and artisanal exploitation permits." |  |  |  |  |
| **Chad** | "Chad's Law No. 36 of 1994 specifies that forests on public land belong to the state, and mandates forest conservation measures." |  | "The Code permits individuals and communities to obtain rights to land that they have reforested or regenerated." | "Private land owners are the owners of trees planted on their land." "By implication, forests on private land are subject to the terms and conditions of the private land rights." |  |
| **Congo** | "Under the current Republic of the Congo Constitution, natural resources, including forests, are State property." "Although the Congolese Forest Code still separates national forest estates from private forest estates, it maintains a basic role of defining, implementing, and enforcing forest policy, and preserving forest stands." |  |  | "Republic of the Congo forests are divided into either private or state-owned forests." "However, the State grants logging rights for these lands to private entities." |  |
| **Costa Rica** | "The Forestry Law is strongly conservationist: Forests within national reserves or on State Property are patrimony of the State (Art. 13) and harvesting them is prohibited (Art. 1). Converting forests on private land to other uses is also prohibited (with certain limited exceptions via permit) (Art. 19). " | "Art. 12 gives Regional Environmental Councils a limited role in decentralised forestry management (Art. 12). They should guide the forest sector locally and can authorise the harvesting of up to 5 trees per year per hectare from agricultural land (Art. 27)." |  | "Harvesting of wood from private forests is only allowed if there is a management plan in place (Art. 20) certified by a forestry engineer (Regente Forestal) that is a member of the College of Agricultural Engineers (CIAgro). " |  |
| **Democratic Republic of Congo** | "State owns all forestland and is responsible for managing the forest resources." |  | "The 2002 Forest Code recognizes indigenous use-rights to forests but does not delineate use rights or processes for certifying and managing community forests." |  |  |
| **Dominican Republic** | "Under Dominican Republic, all land must be registered; all unregistered land is considered state land." "The Environmental and Natural Resources Law, No. 64-00 (2000) governs the Dominican |  |  | "The current Constitution of the Dominican Republic, which was adopted in 2010, recognizes and guarantees the right to own private property, |  |

| | | | | | |
|---|---|---|---|---|---|
| | Republic’s environment and natural resources, including forests and related natural resources." | | | and provides that the state shall promote the acquisition of property, especially titled real property." "Ownership rights include the right to use the land, to exclude others from the land, and the right to sell, lease and mortgage the land." | |
| **Ecuador** | "Indigenous communities and the state are the primary forest owners in Ecuador, although many private individuals also claim forestland rights, and land rights conflicts are common." "As a result, management categories overlap and possession/management rights are often unclear between the state and others (including indigenous and ancestral peoples, farming communities and settlers)." | "In 1999, with the recognition that the state had limited resources and capacity to maintain forest resources, the GOE adopted the Strategy for Sustainable Forestry Development (SNTCF). It directed the Ministry of Environment to delegate to civil society and the private sector all forest-related functions. This has divided the country into 10 regional forestry districts, which have had operational and budgetary autonomy." | "Though almost all of Ecuador‘s forests are held in private or communal possession, an estimated 50% of these lands have unresolved land tenure issues." "Indigenous groups control approximately five million hectares of natural forest in the northwest and eastern lowlands. Though entire communities may hold title to communal lands, these lands are not necessarily used collectively. Communal forestland use is determined internally within the local community. Wood companies and traders must acquire a permit from a community representative in order to proceed with timber extraction (FAO 2006)." | "Though almost all of Ecuador‘s forests are held in private or communal possession, an estimated 50% of these lands have unresolved land tenure issues." "Ecuadorian law has permitted the transfer of public forests to private parties, which promotes land clearing in order to achieve land tenure." | |
| **El Salvador** | "Thirty-one percent are under public ownership and managed by the state (Mongabay 2010)." | | "According to 2005 statistics, nearly 70% of El Salvador’s forests are privately owned by individuals, businesses or local indigenous or tribal communities." | "According to 2005 statistics, nearly 70% of El Salvador’s forests are privately owned by individuals, businesses or local indigenous or tribal communities." | |
| **Ethiopia** | "State forests include all forests held by the federal or regional state governments." | "State forests include all forests held by the federal or regional state governments." | "Private forests include all forests outside state control and include those held and managed by individuals and groups, including community forest associations (USAID 2008)." "The land remains state-owned but the constitution affirms the | "Private forests include all forests outside state control and include those held and managed by individuals and groups, including community forest associations (USAID 2008)." | |

| | | | | | |
|---|---|---|---|---|---|
| | | | right of access to land for every adult." | "The land remains state-owned but the constitution affirms the right of access to land for every adult." | |
| **Ghana** | "The stools own timber trees, yet the Concession Act of 1962 vested all these to the President to administer in trust for the stools." "Generally forest tenure is tightly tied to customary land tenure. However, even customary "owners" of land are not allowed access to forest reserves unless they have proper documentation and permits from the GOG's Forestry Services Division." | | "The stools own timber trees, yet the Concession Act of 1962 vested all these to the President to administer in trust for the stools. However, even customary "owners" of land are not allowed access to forest reserves unless they have proper documentation and permits from the GOG's Forestry Services Division. The Ministry is meant to liaise between customary landowners and the national governments, promote local communities' participation in forest management, develop capacity in the public sector, and review national forest policies and law (GhanaWeb 2011; GOG 2011a)." "Generally forest tenure is tightly tied to customary land tenure." | "Customary rules governing forest tenure give fewer rights to immigrant and tenant farmers (Boakye and Baffoe n.d.). Rights to timber resources will not be granted on land with farms or forest plantations, land where individual or group owners have grown timber, or land that is subject to alienation holdings." "Customary rules governing forest tenure give fewer rights to immigrant and tenant farmers (Boakye and Baffoe n.d.)." | |
| **Guatemala** | "Forests are located on state, municipal, communal, and private lands, and within protected areas (Ferroukhi and Echeverría 2003; GOG 1973)." "Forests on protected land can be within any of the categories above. Because they are within the boundaries of protected areas, their use is limited. The National Council of Protected Areas (CONAP) determines the standards and grants use-permits (Ferroukhi and Echeverría 2003)." | | "Municipal forests are on municipal lands and are administered by the municipal government. Municipalities lease these lands to residents for agricultural purposes (Ferroukhi and Echeverría 2003). Community groups administer communal forests and decide norms based on custom. Sometimes municipalities will transfer responsibility for use and management of municipal forests to the community via local agreements or involve co-management (Ferroukhi and Echeverría 2003)." "Community groups administer communal forests and decide norms based on custom. Sometimes municipalities will transfer responsibility for use and management of municipal forests to the community via local agreements or involve co-management (Ferroukhi and Echeverría 2003). In response to public pressure, the government now supports concession contracts for both industry and communities | "Private forests constitute 38% of total forest area. Forests on private land belong to the owners. Many privately owned forests have been cleared for grazing or coffee-cultivation. Corporations use private forests for wood production (Stoian and Road 2006; Ferroukhi and Echeverría 2003; Gibson et al. 2002; Thunberg 2009)." "Municipalities lease these lands to residents for agricultural purposes (Ferroukhi and Echeverría 2003). In response to public pressure, the government now supports concession contracts for both industry and communities in the Maya Biosphere Reserve, Northern | |

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| | | | in the Maya Biosphere Reserve, Northern Peten, in recognition of the fact that private logging concessions had been managing forests poorly." | Peten, in recognition of the fact that private logging concessions had been managing forests poorly." | |
| **Guinea** | "The Forestry Code divides Guinea's forestland into three categories: (1) state forests; (2) forest areas of decentralized collectives; and (3) unclassified forest areas." "These government institutions charged with protecting forest resources face challenges in identifying the forest classification (e.g., classified, protected) and applying and enforcing appropriate regulations." | | "The Forestry Code divides Guinea's forestland into three categories: (1) state forests; (2) forest areas of decentralized collectives; and (3) unclassified forest areas." "The Forestry Code recognizes the customary rights of communities living within or close to forests. Under customary law, communities with rights to forestland or land adjacent to forests generally have rights to use the land and forest products." | | |
| **Haiti** | "The Constitution (Article 253) forbids environmental degradation that might upset the ecological balance." | | "The Décret of June 26, 1986 (Décret du 26 Juin 1986) modifies the Rural Code to include the composition of a Council of Rural Administrative Sections (CASER). CASERs are the smallest administrative territorial entity in Haiti and are responsible for encouraging soil conservation and reforestation (GOH Rural Code 1962; GOH Amending Decree 1986)." | "The 1987 Constitution recognizes and guarantees private property." | "However, the Constitution does not define ownership rights to forest." |
| **Honduras** | "Public forests include state-owned forests, forests owned by municipalities (including *ejidos*) and any forests granted in concessions." | | "Public forests include state-owned forests, forests owned by municipalities (including *ejidos*) and any forests granted in concessions." "Indigenous groups have rights to forests on lands that they traditionally inhabit. Because the forest regulations have not yet been promulgated, the extent of their rights is unknown (GOH Forest Law 2007). Public forests include state-owned forests, forests owned by municipalities (including ejidos) and any forests granted in concessions." | "Private forests belong to a person or entity with legitimate title and registration." "Under the law, the IFC (formerly the Sate Forest Administration) grants licenses to individuals or corporations for logging." | |

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| **India** | "Within the constraints of national legislation, forests are managed in each state by a state Forest Department. These state departments act as custodians for the nationally owned forest resource. Each state Forest Department is led by a Chief Conservator of Forest. (GOI 2006; GOI 2009b; Kohli 2018; WRI 2014)." | "Within the constraints of national legislation, forests are managed in each state by a state Forest Department. These state departments act as custodians for the nationally owned forest resource. Each state Forest Department is led by a Chief Conservator of Forest. (GOI 2006; GOI 2009b; Kohli 2018; WRI 2014)." | "While the national government owns most forestry resources in India, states have significant management control over forests, and recent legislation (the 2006 Forest Rights Act) vested forest rights on ancestral lands with traditional forest-dwelling communities. Unclassed Forest (which fall under the jurisdiction of communities and individuals, and include forests that are neither reserved nor protected). (NFAP 2001; FAO 1997; Global Forest Coalition 2010)." | "Unclassed Forest (which fall under the jurisdiction of communities and individuals, and include forests that are neither reserved nor protected). (NFAP 2001; FAO 1997; Global Forest Coalition 2010)." | |
| **Indonesia** | "The overwhelming majority of forested land in Indonesia is classified as state forest and is therefore controlled by the state." | "The new era of decentralization of government authority – from the central government to the district (*kabupaten*) governments – has created more space for *adat* communities to assert rights to at least receive compensation for the removal of trees from their land." | "Although the BAL recognizes the customary land rights – called hak ulayat – of traditional adat communities, including communities living in forests, the recognition applies only to communities that still exist, and only if the interests of the community do not violate interests of the Indonesian state. The new era of decentralization of government authority – from the central government to the district (kabupaten) governments – has created more space for adat communities to assert rights to at least receive compensation for the removal of trees from their land." | "Today, only a small proportion of forests in Indonesia are on privately titled land (Lindsey 1998; Contreras-Hermosilla and Fay 2005)." | |
| **Ivory Coast** | "The forestry domain defined by the Forestry Code is divided between the Permanent Forest Domain (*Domaine Forestier Permanent de l' État*, or DFPE) and the private and community forests (*Domaine Forestier des Particuliers et des Collectivités)*.." | | "The forestry domain defined by the Forestry Code is divided between the Permanent Forest Domain (*Domaine Forestier Permanent de l' État*, or DFPE) and the private and community forests (*Domaine Forestier des Particuliers et des Collectivités)*.." "For example, under the various customary law regimes in Côte d'Ivoire, communities do not allow land to be alienated from the community. This poses problems when customary groups enter into land transactions with migrants or others outside the customary group system who operate under a property rights framework whereby a transfer extinguishes rights of the transferor. | "The forestry domain defined by the Forestry Code is divided between the Permanent Forest Domain (*Domaine Forestier Permanent de l' État*, or DFPE) and the private and community forests (*Domaine Forestier des Particuliers et des Collectivités)*.." "Use in the latter is regulated by customary regimes and the Forestry Code, which allow the collection of traditionally-harvested forestry resources for subsistence needs (GOCI Forest Code 1965; ITTO 2006; ITTO 2009; | |

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| | | | Use in the latter is regulated by customary regimes and the Forestry Code, which allow the collection of traditionally-harvested forestry resources for subsistence needs (GOCI Forest Code 1965; ITTO 2006; ITTO 2009; Cabrera et al. 2010; FAO 2001; Gadji 2003; McCallin and Montemurro 2009; Sidibe and Brady 2010)." | Cabrera et al. 2010; FAO 2001; Gadji 2003; McCallin and Montemurro 2009; Sidibe and Brady 2010)." | |
| **Jamaica** | "According to 2000 data, of all forest-covered land, 65% is privately owned, 28% is publicly owned, and the remaining 7% is subject to other types of ownership (GOJ 2006a)." | | | "According to 2000 data, of all forest-covered land, 65% is privately owned, 28% is publicly owned, and the remaining 7% is subject to other types of ownership (GOJ 2006a)." | |
| **Kenya** | "Ownership of forests are categorized by State Forests managed by the Kenya Forest Service, Local Authority Forests, and private forests owned and managed by an individual, association, institution or corporate entity." "Even though the private landowner "owns" the trees, the President under Section 34 of the Forest Act has the powers to declare a tree, species or family of trees protection in the country or in specific areas, in which case a person is prevented from felling, damaging or removing any trees so declared." | | "All forests, other than private forests and local authority forests, are vested in the State, unless otherwise provided for by law or contract. Local authority forests (i.e., forests found on trust lands and lands under the jurisdiction of local authorities, including urban forests)." "Customary rights to forest products are allowed, as long as the products are not offered for sale (Ludeki et al. 2006). Members of forest communities are encouraged to form associations registered under the Societies Act and apply to participate in forest conservation and management." | "Ownership of forests are categorized by State Forests managed by the Kenya Forest Service, Local Authority Forests, and private forests owned and managed by an individual, association, institution or corporate entity." | |
| **Laos** | "The Forestry Law provides that natural forest and forestland is the property of the national community, managed by the state." "Lao PDR recognizes a range of forest-resource tenure rights: rights to use state-managed forestland; customary use rights; communal use rights; leases and concessions held by private entities; and open access." | | "Lao PDR recognizes a range of forest-resource tenure rights: rights to use state-managed forestland; customary use rights; communal use rights; leases and concessions held by private entities; and open access." | "Lao PDR recognizes a range of forest-resource tenure rights: rights to use state-managed forestland; customary use rights; communal use rights; leases and concessions held by private entities; and open access." | |

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| **Liberia** | "The National Forestry Reform Law provides that all forest resources belong to the state, except forest resources located in communal forests, and forest resources developed on private or deeded land through artificial regeneration." | | "The National Forestry Reform Law provides that all forest resources belong to the state, except forest resources located in communal forests, and forest resources developed on private or deeded land through artificial regeneration." | "The National Forestry Reform Law provides that all forest resources belong to the state, except forest resources located in communal forests, and forest resources developed on private or deeded land through artificial regeneration." | |
| **Madagascar** | "Under Madagascar's formal law, all forests except for those on titled land are state property. Villagers do not have the right to access and use forests without state permission." | | "Access and use rights are only authorized within sustainable-use protected areas. In some areas, customary law prevails and communities apply their own rules and regulations in regard to limiting access to forest resources and establishing use norms (RRI 2015). While the state is the owner of all forests, co-management between the state and local communities was enabled by the 1996 Gestion Locale Sécurisée (GELOSE) Law (Law No. 96-025), through which Madagascar became one of the first countries in the southern hemisphere to establish a legal framework for community-based natural resource management (World Bank 2015; Reynolds and Flores 2009; USAID 2014; Evers et al. 2006)." | | |
| **Malawi** | "Between 51% and 65% of Malawi's forests are on customary land; 21% to 22% are on state land (protected areas and agricultural schemes); and the balance is on private freehold and leasehold estates (GOM 2001; Mwase et al. 2006)." | | "At independence in 1964, Malawi's land was designated as under private freehold, public, or customary ownership. Between 51% and 65% of Malawi's forests are on customary land; 21% to 22% are on state land (protected areas and agricultural schemes); and the balance is on private freehold and leasehold estates (GOM 2001; Mwase et al. 2006)." "The 2005 Standards and Guidelines for Participatory Forestry in Malawi provide the basis for all community-level forestry interventions, including tree planting and comanagement of state forest reserves/plantations. The Standards and Guidelines set out each step of the community-based forest | "At independence in 1964, Malawi's land was designated as under private freehold, public, or customary ownership. Between 51% and 65% of Malawi's forests are on customary land; 21% to 22% are on state land (protected areas and agricultural schemes); and the balance is on private freehold and leasehold estates (GOM 2001; Mwase et al. 2006)." "Between 51% and 65% of Malawi's forests are on customary land; 21% to 22% are on state land | |

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| | | | management process. Local forest- dependent communities register as local forest organizations, develop forest management plans, and enter into management and benefit-sharing agreements with the government (FGLG 2008)." | (protected areas and agricultural schemes); and the balance is on private freehold and leasehold estates (GOM 2001; Mwase et al. 2006)." | |
| **Mali** | "Under the 1995 Forest Code the state owns all “vacant” land, including forests and fallows older than 10 years." | | "Forest Code identifies three types of forests: (1) state forests; (2) forests run by territorial communities; and (3) forests run by private individuals." | "Individuals have rights to forests on land held under customary tenure." | |
| **Mexico** | "Of the total forest surface, about 70% is community property (belonging to ejidos and indigenous comunidades), 26% is private property (small-scale landowners), and the remaining 4% is government property (Spiric 2015)." "The Federal Ombudsman for Environmental Protection (PROFEPA) has the power to conduct audits to ensure communities are complying with their permits (Guerra 2015; Hodgdon and Murrieta 2015)." | | "Of the total forest surface, about 70% is community property (belonging to ejidos and indigenous comunidades), 26% is private property (small-scale landowners), and the remaining 4% is government property (Spiric 2015)." "An increasing number of forest communities have assumed full control over their forests through their community forest enterprises (CFE). Forests owned by communities are managed through institutional arrangements that vary from community to community." | "Of the total forest surface, about 70% is community property (belonging to ejidos and indigenous comunidades), 26% is private property (small-scale landowners), and the remaining 4% is government property (Spiric 2015)." "Of the total forest surface, about 70% is community property (belonging to ejidos and indigenous comunidades), 26% is private property (small-scale landowners), and the remaining 4% is government property (Spiric 2015)." | |
| **Mozambique** | "Mozambique’s natural forest and wildlife resources are the property of the state." "The Forestry Law authorizes the government to impose penalties—including fines, imprisonment, and compulsory restoration of damaged forestland—for violations of the law and supporting regulations." | | "Individuals and groups can obtain rights to use and benefit from the forest through occupancy or specific authorization. There is no direct and consequent connection between the rights to land and the rights to forestry resources. Local communities have the right to use forest resources to meet subsistence needs without payment of any fee and can designate forest areas of cultural significance (GOM Forestry Law 1999)." | "Individuals and groups can obtain rights to use and benefit from the forest through occupancy or specific authorization." | |

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| **Namibia** | "Forestland and forest resources are the property of the state." | | "Communities can apply for rights to manage and use forest products and forest land, and collect and retain fees for use of the forest by others in accordance with management plans. Inhabitants of communal land are free to use unclassified forests and take forest products for household use in accordance with customary law." | "Individuals and groups can obtain rights to use and benefit from the forest through occupancy or specific authorization." | |
| **Nicaragua** | "An estimated 55% of forestland is privately held; 25% is held by indigenous communities; 13% is state-owned; and the balance is held by municipalities and local governments (GON 2011; Mongabay 2010)." "However, the authority to issue permits for logging is held by the central government: private forestland owners must obtain household permits from the National Forest Institute (INAFOR) to log small amounts of timber, and a management plan is required for concessions to log larger amounts." | | "An estimated 55% of forestland is privately held; 25% is held by indigenous communities; 13% is state-owned; and the balance is held by municipalities and local governments (GON 2011; Mongabay 2010)." "Under the 1997 Municipalities Law, local municipalities have the authority to develop, conserve, and control the use of natural resources, including timber and other forest products." | "An estimated 55% of forestland is privately held; 25% is held by indigenous communities; 13% is state-owned; and the balance is held by municipalities and local governments (GON 2011; Mongabay 2010)." "However, the authority to issue permits for logging is held by the central government: private forestland owners must obtain household permits from the National Forest Institute (INAFOR) to log small amounts of timber, and a management plan is required for concessions to log larger amounts." | |
| **Niger** | "Forest reserves are controlled by the state through its technical service." | | "The 1993 Rural Code permits the devolution of the management and use of woodlands from the central government to communes, and in some cases to groups of local people through rural concessions (Delville 2000)." | | |
| **Nigeria** | "Access to Nigeria's protected areas and use of forest resources in protected areas is restricted. Many forest reserves, which are administered by the Department of Forestry, have been converted into plantations for revenue generation." | "Each state has a separate forest law but most are decades old, and the central government remains responsible for federal forestland, including national parks. State-level forestry offices are authorized to enforce state forestry laws, but enforcement tends to be weak." | | "The unclassified forest land is rapidly being encroached by farmers who gain income and customary land rights by clearing the land, selling the timber, and cultivating the land (ARD 2002; EC-FAO 2003; Aribigbola 2007; Oluwasanmi 1966). " | |

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| **Panama** | "ANAM exerts state authority to regulate the use of natural resources by issuing licenses and permits." | | "In the case of indigenous communities, "trees or forests established through plantation or reforestation can be exploited after notification to ANAM, as long as they are registered with ANAM (Res JD 05-98, Article 50)." Therefore, registering artificial forests with ANAM is a key step in their legal utilization." | "Therefore, it is possible for land to be private property, and at the same time be considered part of the State forest assets or patrimony, if it has natural forests. In the case of "artificial forests on private property" planted at the owner's expense, the "owner" is allowed to utilize them when he or she deems convenient, with the exception of forests protecting watersheds." | |
| **Paraguay** | "Some land is public land, such as some land in the protected areas and the lands alongside roads and power lines." | | "It is not clear how much land is currently held legally by indigenous peoples in Paraguay or the Chaco specifically, or how much land is used and/or claimed by them under customary tenure arrangements alone. In the case of the presence of an indigenous community, a public audience (audiencia pública) is required for the process to continue, though it is unclear how often this process is invoked." | "Today, more than 95 percent of land in Paraguay is held as private property.81 In the Chaco, most land is privately owned, principally by individuals, corporations, and cooperatives." | |
| **Peru** | "The Peruvian Constitution states that all natural resources, including forests, belong to the State. According to the Constitution, ownership rights to natural resources (including forests) belong to the state." "According to the Constitution, ownership rights to natural resources (including forests) belong to the state." | | "Peasant and native communities have exclusive use rights over the assets and services of forest ecosystems and other ecosystems within their lands and within other areas as designated by the State. However, in order to use the forest resources and wildlife in their lands, communities must request permission from forestry and wildlife authorities." | "Most forests are located on public lands, and the state may grant use rights to the private sector through time-limited concessions. Publicly owned forest land includes permanent production forests, conservation concessions, natural protected areas, and state reserves. Privately owned categories include land held by Amazonian indigenous communities, Andean peasant communities, private conservation areas, and private agriculture plots (World Bank 2006b; Portilla and Eguren 2007)." | |

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| **Philippines** | "Under the 1987 Constitution all forest lands and natural resources belong to the State (Art. 7, Sec. 2)." "State tenure, notably in protected areas and watershed reservations, are generally for purposes such as biodiversity conservation, education and research. In the past 25 years, CBFM (and various joint venture, co-production and production-sharing instruments) has been viewed as the most effective strategy for achieving sustainable forest management and for addressing the problems plaguing the Philippine forestry industry." |  | "Communal Forests are forestlands not exceeding 5000 hectares set aside by the government for local government use and subject to an approved sustainable operations plan." | "In the past, forest rights granted by the government to the private sector were principally for forest-resource utilization and commercial exploitation (concessions, licenses or permits). Prior to the 1987 Constitution, logging rights were often granted to the elite. All tenure rights are granted for a 25-year period, renewable for the same period." |  |
| **Rwanda** | "Under the 2013 Forest Law, that forests may be owned by either the state, a district or by a private individual." "The law gives to the government the right to suspend forest harvesting to improve forest management, to allow for regeneration of forests and to conserve the environment and/or biodiversity." | "Under the 2013 Forest Law, that forests may be owned by either the state, a district or by a private individual." "District forests may be managed by individuals, associations, companies, cooperatives or NGOs. District Councils grant these rights to selected entities (GOR Forest Law 2013)." |  | "Under the 2013 Forest Law, that forests may be owned by either the state, a district or by a private individual." |  |
| **Senegal** | "All forestland is owned by the state, with authority to manage the resources devolved to subnational levels subject to compliance with the regulatory framework governing the forest type and permissible exploitation and the preparation of forest management agreements." |  | "The 1998 Forest Code provides that regional authorities and rural communities can exercise a variety of rights regarding forests, including demarcating forests and mapping forest uses and managing forest resources." |  |  |

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| **Sierra Leone** | "Forests can be owned by the state or private parties, or fall within chieftaincy land. The current extent of state-owned forestland is unknown. The state owns most of the land designated as forest reserves and nationally protected areas, but some percentage of land is also privately held or within chieftaincy land (FAO 2005a; Chemonics et al. 2007)." | | "Forests can be owned by the state or private parties, or fall within chieftaincy land. The state owns most of the land designated as forest reserves and nationally protected areas, but some percentage of land is also privately held or within chieftaincy land (FAO 2005a; Chemonics et al. 2007)." | "Forests can be owned by the state or private parties, or fall within chieftaincy land." | |
| **South Sudan** | "Under the current legal framework, the GoSS has ownership of national forest reserves on behalf of all the people of South Sudan." | "Forests are managed in partnership with State Governments, which take ownership of state forest reserves on behalf of all people of the State." | "Community forests are governed by customary law and administered by traditional leaders and local government. Under the Land Act, while the government may take, reserve or reallocate forest land for a range of public uses, compensation is also guaranteed to any person whose right of occupancy, ownership or recognized longstanding occupancy of customary land is revoked (GoSS 2011c; GoSS 2011f; GoSS 2009a)." "The traditional authority within a specific community is empowered to allocate customary rights to land, and for forestry purposes such as the collection of wood for fencing and fuel, harvesting of non-timber forest products and hunting for household consumption. The traditional authority is required to notify the County Land Authority or the Payam Land Council prior to allocating customary land rights (GoSS 2010; TerrAfrica 2010)." | "Private sector plantations for the licensed trade of forestry products." | |
| **Sudan** | "All unregistered forestland is considered state land over which the National Forests and Natural Resources Corporation has authority (UNEP 2007; FAO 2003)." "Forest tenure types include protected areas, forest reserves (federal, state and institutional), community forests and private forests (including corporate forests)." | "The FRNRA assigns management of federal forest reserves to the NFRNRC, and management of state forest reserves to forest administrations in the states in accordance with NFRNRC policies and technical plans. States are entitled to receive 40% of revenues generated within their territory from forest resources and the | "Private entities, NGOs and communities can apply for concessions for forest areas, including land in reserves." | "Private entities, NGOs and communities can apply for concessions for forest areas, including land in reserves." | |

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|  |  | Federal Government receives the remaining 60%." |  |  |  |
| **Tanzania** | "A recent government inventory of forests finds the distribution of forest ownership is as follows: central government land, 34 percent, local government land 6.5 percent; village land 45.7 percent; private land, 7.3 percent; and unknown less than 3 percent." | "District forest officers responsible for enforcement report to local district authorities as opposed to the central level FBD. Under the Local Government (District) ." | "Upon provision of an acceptable Village Forest Management Plan (VFMP), control and ownership of all the forest resources devolves to the village government. This gives communities the right to harvest and sell timber and forest products, as well as to undertake patrols (including arresting and fining offenders) to keep out illegal users. Villages are exempted from government taxes on the forest products, including major timber species (or “reserved tree” species), and therefore can claim royalty revenue that previously would have gone to the government (GOT 2015b). Together these developments have brought more than half a million hectares under community protection and since 1995 more than five hundred VLFRs have been created by communities."<br>"This gives communities the right to harvest and sell timber and forest products, as well as to undertake patrols (including arresting and fining offenders) to keep out illegal users. Villages are exempted from government taxes on the forest products, including major timber species (or “reserved tree” species), and therefore can claim royalty revenue that previously would have gone to the government (GOT 2015b)." | "A recent government inventory of forests finds the distribution of forest ownership is as follows: central government land, 34 percent, local government land 6.5 percent; village land 45.7 percent; private land, 7.3 percent; and unknown less than 3 percent." |  |

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| **Thailand** | "The state owns all forests in Thailand. Trees on private land are considered private property (ITTO 2005; FAO 2005)." |  | "The government launched a program in 1981 to grant 5-year use licenses (STK) recognizing cultivation rights within the forests. These certificates cannot, however, be converted into a title deed or Certificate of Use and can only be transferred by inheritance. If licensees violate the terms of the license, the state can take the land without payment of compensation. The licenses are criticized by licensees and observers as potentially increasing insecurity of tenure because they are granted for very short terms and give the state the authority to monitor land-use and seize land (USDOS 2006; USDOS 2008; Childress 2004; Giné 2004; *Bangkok Post* 2010c). While the Constitution states that traditional and local communities have the right to participate in natural- resources management, the details on how this shared management relationship would work and what resources local communities have the right to manage are still under debate." | "Trees on private land are considered private property (ITTO 2005; FAO 2005)." |  |
| **Uganda** | "About 70% of the forest is on private land, mostly woodland. The remaining forest is held in trust by the government for the citizens—15% in Central Forest Reserves and 15% in National Parks and Wildlife Reserves." | "The district forestry officials are responsible for regulating the cutting of trees on private land and overseeing the management of Local Forest Reserves. The Environment Minister, however, has requested that district authorities—specifically, the district forestry officials—should no longer be allowed to grant permits for cutting trees because the permits are used by loggers to cut down trees in Central Forest Reserves (Tenywa 2008a)." | "The National Forestry Authority (NFA) is promoting the development of Community Forest Management. Community groups must register as a Communal Land Association (CLA) under the terms of the Land Act. Registered groups can then apply to the NFA for a Declaration of a Community Forest under the National Forestry and Tree Planting Act." | "About 70% of the forest is on private land, mostly woodland. The remaining forest is held in trust by the government for the citizens—15% in Central Forest Reserves and 15% in National Parks and Wildlife Reserves. The government is encouraging private forest owners to register their forests—under the National Forestry and Tree Planting Act (2003)—in order to protect their rights of use (Mwima et al. 2004)." |  |

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| **Vietnam** | "Under Vietnam's 2003 Law on Land, all land, including forestland, belongs to all the people and is managed by the state." | | "The government, through its Provincial People's Committees, began piloting a community forest management program in 2004, allocating forest tenure and accompanying responsibilities to communities living on forestland. The project has remained small, and only a minor percentage of the privately held forestland has been allocated for community management (approximately 17,000 hectares to 64 villages). The government intends to allocate another 2.5 million hectares (another 18% of Vietnam's current forestland) to households and communities (RECOFTC 2011; FSIV 2009; World Bank 2010b; World Bank 2012d)." | "However, forestland is allocated to private entities, including households, for long-term tenure agreements, typically for 50 years with a possible extension. About 24% (3,311,280 hectares) of Vietnam's forestland is formally allocated or leased to private entities, including more than 1.1 million organizations, households and individuals. About 90,000 households and individuals have contracts to protect, plant or regenerate natural, special-use and protection forests." | |
| **Zambia** | "While others are owned directly by the State." "At the same time, all land under private leasehold tenure is classified as State Land as are all privately owned forests (individual, industry and other private)." | | "Other tracts of forests are under the oversight of traditional leaders or customary authorities, while others are owned directly by the State. The concept seeks to devolve control over a demarcated forest to a community as long as that community maintains, protects, develops and uses the forest in a sustainable way that promotes subsistence rights and sustainable sale of forest products. The creation of a Community Forest follows a process of boundary negotiation, establishment and recognition of a management group, management planning and development of rules, creation of a Community Forest Agreement and approval by the Forest Department, followed by implementation. " | "Some forests are owned by individuals, firms or industries and other private entities such as non-governmental organizations, and considered under private ownership." "At the same time, all land under private leasehold tenure is classified as State Land as are all privately owned forests (individual, industry and other private). Both trust and reserve lands are regarded as customary land and administered by traditional chiefs and their headmen who control land allocation." | |
| **Zimbabwe** | "Land within communal areas is vested in the President, and the Rural District Councils (RDCs) allocate land for occupancy and use." "However, such forest resources can be exploited on behalf of the state by the Minister. In some areas, Rural District Councils can grant outsiders concessions to use forest products for | "However, such forest resources can be exploited on behalf of the state by the Minister. In some areas, Rural District Councils can grant outsiders concessions to use forest products for commercial | "Under the law, exploitation of forest resources in communal areas by inhabitants of communal areas is limited to household consumption. Local individuals can only use forest resources for their personal use in accordance with a license, permit or other agreement." | "Commercial timber extraction in communal areas is overseen by the Rural District Councils (RDCs). Based on a forest inventory approved by the Forestry Commission, an RDC may call for commercial tenders for exploitation, which | |

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| | commercial purposes (Shumba 2001a)." | purposes (Shumba 2001a)." | | also requires an environmental assessment." | |

**Table A.2.** An overview of the USAID Country Profile information from which the right provisioning to national, regional, local and individual governing bodies is determined for the right of enforcement. Enforcement is defined as the formal right to enforce (by-) laws on forest use and protection. Governing bodies have multiple rights at once or may not have a specific rights in forest governance. National governing bodies include ministries but also autonomous government agencies that operate at a national scale. Regional governing bodies operate at a regional level, such as a district or a State. Local governing bodies operate at municipality or village level and may include village or municipality governments and committees, but also NGOs. Finally, individual governing bodies include individual people and companies that operate at a local scale on the forest land or trees that they own, lease or obtain user rights over. The USAID Country Profiles can be found on the following website: https://www.land-links.org/country-profiles/. Information from USAID Country Profiles is only provided about the governing bodies that were found to have the task of Enforcer. The text is not adapted from the original text found in the USAID Country Profiles and should therefore be treated as quotes form the Profiles.

**Right of enforcement**

| | **National** | **Regional** | **Local** | **Individual** | **Unspecified** |
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| **Angola** | "The management of these forests is under the responsibility of the Ministry of Agriculture (MINADR) and Environment (MINAMB) through the IFD Table 5. Contracts or licences provided by the IFD in exploiting timber for charcoaling (Chiteculo et al. 2018)." | | | | |
| **Bangladesh** | "All major forests are owned or controlled by the government (FAO). The Revenue Department of the government owns the unclassed state forests (USF, over 0.73 million ha) but most is under the control of district administrations. The law allows the government to require private forest-land owners to develop and abide by forest management plans or risk loss of the forest land to the state (FAO 2000)." | | | | |

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| **Bolivia** | "The Vice-Ministry of Biodiversity, Environment, Climate Change and Forest Development and Management, together with the Authority for Forests and Land (ABT), share jurisdiction and responsibility over forestlands." | | "The law devolves responsibility for managing forests to municipalities and promotes the sustainable management of forests through design and implementation of forest management plans and deforestation permits. The Constitution also gives indigenous communities located within forest areas the exclusive right to exploit, in accordance with the law, forest resources within those areas. The Constitution further provides that, where indigenous territories overlap with protected areas, traditional practices of the former take priority over the rules established for the latter (GOB Constitution 2009)." | | |
| **Botswana** | "The Department of Forestry and Range Resources is one of the seven different operational departments within the Ministry of Environment, Wildlife and Tourism. The Department is responsible for development and implementation of forest policy, including implementation of community-based forest and rangeland management plans." | | "No separate legal framework governs forest land that is not within Botswana's forest reserves. The vast majority of Botswana's woodlands and forests are on tribal land and are considered open-access resources. Access to and use of forest resources is subject to the Tribal Land Act, which is consistent with customary law (Adams et al. 2003; ROB 2002). Access to forests and use of forest resources on tribal land is governed by the Land Boards, and in some areas, by traditional authorities such as chiefs and headmen (Adams et al. 2003; ROB 2002)." | | |
| **Brazil** | "The Brazilian Constitution stipulates that the federal, state, and municipal governments have the duty for ecological preservation, including that of forests. The Ministry of Environment (MMA), the National | "States and municipalities license activities with impacts restricted to their territories. In practice, there is a struggle among municipal, state, and national environment organizations over the licensing of large-scale activities, and activities that generate more resources for environmental | "States and municipalities license activities with impacts restricted to their territories. In practice, there is a struggle among municipal, state, and national environment organizations over the licensing of large-scale activities, and activities that generate more resources for environmental | | |

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| | Environmental Council (CONAMA), and IBAMA are the primary institutions of forest management." | agencies are often a reason for disputes." | agencies are often a reason for disputes." | | |
| **Burkina Faso** | "The State is responsible for developing a national forest policy and defining the global objectives of that policy." | | | | |
| **Burundi** | "The Ministry of Water, Environment, Territory Management and Urbanism has responsibility for the country's forests." | | | | |
| **Cambodia** | "Article 59 of the Constitution provides that the state will protect the environment, including forests and forest products. The 2002 Forestry Law defines the framework for management, harvesting, use, development and conservation of the forests in Cambodia." | | | | |
| **Cameroon** | "The state is responsible for the protection of the country's forests and sets a standard of maintaining at least 30% of total land area as protected, permanent forest. " | | | | |
| **Central African Republic** | "The Forest Code provides for state ownership of the country's forests and divides the forests into the permanent forest domain and non-permanent forest domain." | | "The state must also consult with the local population, including indigenous communities, before granting a concession for industrial exploitation of the forest." | | |

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| **Chad** | "Chad's Law No. 36 of 1994 specifies that forests on public land belong to the state, and mandates forest conservation measures. " |  |  |  |  |
| **Congo** | "Under the current Republic of the Congo Constitution, natural resources, including forests, are State property." |  |  |  |  |
| **Costa Rica** | "The Forestry Law is strongly conservationist: Forests within national reserves or on State Property are patrimony of the State (Art. 13) and harvesting them is prohibited (Art. 1). Converting forests on private land to other uses is also prohibited (with certain limited exceptions via permit) (Art. 19). " |  |  |  |  |
| **Democratic Republic of Congo** | "State owns all forestland and is responsible for managing the forest resources." |  | "The local forestry department is authorized to issue these permits at the area of extraction and requires inspections at production sites. The local forestry department is also responsible for issuing sale permits to charcoal merchants and collecting tax. " |  |  |
| **Dominican Republic** | "Responsibility for the environment and for natural resource management, including forest management, is consolidated under the Ministry of the Environment and Natural Resources." |  |  |  |  |

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| **Ecuador** | "The Ministry of Environment oversees protected areas and the Public forests, while INDA, which is under the Ministry of Agriculture and Livestock, oversees areas outside the domain of the ministry." | "In 1999, with the recognition that the state had limited resources and capacity to maintain forest resources, the GOE adopted the Strategy for Sustainable Forestry Development (SNTCF). It directed the Ministry of Environment to delegate to civil society and the private sector all forest-related functions. This has divided the country into 10 regional forestry districts, which have had operational and budgetary autonomy." | "Indigenous groups control approximately five million hectares of natural forest in the northwest and eastern lowlands. Though entire communities may hold title to communal lands, these lands are not necessarily used collectively. Communal forestland use is determined internally within the local community. Wood companies and traders must acquire a permit from a community representative in order to proceed with timber extraction (FAO 2006)." | | |
| **El Salvador** | "Under the Constitution, the state is required to ensure sustainable development by protecting natural resources and environmental integrity (GOE Constitution 1983).The Ministry of Agriculture and Animal Husbandry and the Ministry of Environment and Natural Resources (MARN) are the primary government institutions responsible for the administration of the forest sector (Forest Carbon Partnership Facility 2008)." | | | | |
| **Ethiopia** | "The Forestry and Wildlife Conservation and Development Team within the MoARD is responsible for forest policy and oversight of forest management by regional governments." | | | | |

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| **Ghana** | "The Forestry Commission is a semi-autonomous agency that replaced the former Forestry Department, brought all relevant public agencies under the same structure and streamlined forest management services." | | "The 1992 Constitution of Ghana upholds the authority of local chiefs to manage and allocate land and divides land into both public and custom-ary tenures. Under the 1962 Concession Act and the 1992 Constitution the concessions gained by government are shared with stools and local government (FAO 2004; GOG 1994)." | | |
| **Guatemala** | "The National Institute of Forests (INAB) has jurisdiction over forests that are not in protected areas. INAB is an autonomous, decentralized independent agency with offices in nine regions and 31 sub-regions." | | "There are 16 Community Forest Enterprises (CFEs) (2006 data). Eleven of these are organized under FORESCOM (Forest Services Community Business, or Empresa Forestal Comunitaria de Servicios del Bosque S.A.), which provides CFEs with technical and business services. FORESCOM is a community forestry business focused on balancing the protection of ecosystems with economic development through concessions." | | |
| **Guinea** | "Very recent restructuring of Ministries now puts forest-related activities within the Ministry of Environment and Sustainable Development. These government institutions charged with protecting forest resources face challenges in identifying the forest classification (e.g., classified, protected) and applying and enforcing appropriate regulations." | | "It devolves control of the forest to the country's elected rural councils, supported by forestry service representatives." | | |

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| **Haiti** | "The Ministries of Agriculture, Tourism, Environment, and Planning all attempt to regulate forest resources, with limited success (Regan 2003)." | | "The Décret of June 26, 1986 (Décret du 26 Juin 1986) modifies the Rural Code to include the composition of a Council of Rural Administrative Sections (CASER). CASERs are the smallest administrative territorial entity in Haiti and are responsible for encouraging soil conservation and reforestation (GOH Rural Code 1962; GOH Amending Decree 1986)." | | |
| **Honduras** | "The Institute of Forest Conservation and Development (ICF), created by the 2007 Forest Law, replaced the State Forest Administration-Honduran Forest Development Corporation (AFE-COHDEFOR). ICF promulgates regulations, executes national policy on forest development and conservation and issues permits for forest extraction to corporations and individuals. It is specifically charged with implementing the National Forest Program (PRONAFOR) (Global Witness 2009; GOH Forest Law 2007; GOH 2009b)." | | | | |
| **India** | "While the national government owns most forestry resources in India, states have significant management control over forests, and recent legislation (the 2006 Forest Rights Act) vested forest rights on ancestral lands with traditional forest-dwelling communities." | "While the national government owns most forestry resources in India, states have significant management control over forests, and recent legislation (the 2006 Forest Rights Act) vested forest rights on ancestral lands with traditional forest-dwelling communities. These state departments act as custodians for the nationally owned forest resource. Each state Forest Department is led by a Chief Conservator of | | | |

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| | | Forest. (GOI 2006; GOI 2009b; Kohli 2018; WRI 2014)." | | | |
| **Indonesia** | "The overwhelming majority of forested land in Indonesia is classified as state forest and is therefore controlled by the state." | "The new era of decentralization of government authority – from the central government to the district (*kabupaten*) governments – has created more space for *adat* communities to assert rights to at least receive compensation for the removal of trees from their land." | | | |
| **Ivory Coast** | "SODEFOR and the Ivoirian Parks and Reserves Office (*Office Ivoirien des Parcs et Réserves* or OIPR) are entrusted with the management of protected forests. SODEFOR is a state company established by Decree No. 93-106 of 1993 which in effect renamed the former Forest Plantation Development Society, which was created in 1966 to promote reforestation." | | | | |
| **Jamaica** | "The Forestry Department is the lead agency for forestry management and also plays a critical role in watershed management (GOJ 2001)." | | | | |

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| **Kenya** | "All forests, other than private forests and local authority forests, are vested in the State, unless otherwise provided for by law or contract." | | "The Act allows for Kenyans and forest communities to participate in the implementation and monitoring of the Forests Act and the management of their forests as members of Community Forest Associations (CFAs); as representatives appointed to the Forest Conservation Committees; as representatives appointed to the Board of the Kenya Forest Service; and as individuals (FAN n.d.). Under the law, communities are supposed to make up close to 50 percent of representation in the Forest Conservation Committee. The law also provides for community representation on the Board of the Kenya Forest Service (FAN n.d.)." | "The Act allows for Kenyans and forest communities to participate in the implementation and monitoring of the Forests Act and the management of their forests as members of Community Forest Associations (CFAs); as representatives appointed to the Forest Conservation Committees; as representatives appointed to the Board of the Kenya Forest Service; and as individuals (FAN n.d.)." | |
| **Laos** | "The Forestry Law provides that natural forest and forestland is the property of the national community, managed by the state." | | | | |
| **Liberia** | "The National Forestry Reform Law provides that all forest resources belong to the state, except forest resources located in communal forests, and forest resources developed on private or deeded land through artificial regeneration." | | | | |

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| **Madagascar** | "Under Madagascar's formal law, all forests except for those on titled land are state property." | | "Access and use rights are only authorized within sustainable-use protected areas. In some areas, customary law prevails and communities apply their own rules and regulations in regard to limiting access to forest resources and establishing use norms (RRI 2015). While the state is the owner of all forests, co-management between the state and local communities was enabled by the 1996 Gestion Locale Sécurisée (GELOSE) Law (Law No. 96-025), through which Madagascar became one of the first countries in the southern hemisphere to establish a legal framework for community-based natural resource management (World Bank 2015; Reynolds and Flores 2009; USAID 2014; Evers et al. 2006). " | | |
| **Malawi** | "The Forestry Act governs the management and use (licensing) of forests on public, private and customary land." | "The District Forestry Offices take lead responsibility for dissemination of forest resource information to the public, comanagement of forestry resources, fire prevention, and for customary land not covered by a management agreement." | "On customary forest land, management is decentralized to Village Natural Resource Management Committees (VNRMCs) that take lead responsibility for licensing activities within a demarcated "Village Forest Area" covered by a management agreement (GOM 1997). VNRMCs take lead responsibility for licensing activities within a Village Forest Area covered by a management agreement. To date, few Village Forest Areas have been created (GOM 2001; Gowela and Masamba 2002; Place and Otsuka 2000)." | | |
| **Mali** | "The Ministry of Environment includes regional Offices for the Conservation of Nature (DRCN). The DRCN is the decentralized forestry service responsible for forest | "The Ministry of Environment includes regional Offices for the Conservation of Nature (DRCN). The DRCN is the decentralized forestry service responsible for forest conservation, training agents in forest law, supporting village | "The customary institutions, which usually operated at the village level, established rules of access, organized policing of the forest, and punished infringements by confiscating forest products and tools, | | |

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| | conservation, training agents in forest law, supporting village management committees, and providing technical assistance in forest management." | management committees, and providing technical assistance in forest management." | levying fines, or ostracizing offending persons. Government decentralization and regulation has weakened customary institutions in many areas." | | |
| **Mexico** | "The Federal Ombudsman for Environmental Protection (PROFEPA) has the power to conduct audits to ensure communities are complying with their permits (Guerra 2015; Hodgdon and Murrieta 2015)." | | "An increasing number of forest communities have assumed full control over their forests through their community forest enterprises (CFE). Forests owned by communities are managed through institutional arrangements that vary from community to community." | | |
| **Mozambique** | "The National Directorate of Forests (DINAF) of the MITADER is responsible for the issuing of licenses, protection, supervision, conservation and management of forests and the monitoring of consumption by communities (Presidential Decree No. 13/2015)." | | | | |
| **Namibia** | "The Directorate of Forests within the Ministry of Agriculture, Water and Forestry is responsible for the forests. The Directorate is divided into two divisions: Forest Management and Forest Research. The Forestry Council includes Ministry staff and one person nominated by the Council of Traditional Leaders (Hailwa 2002)." | | "The Directorate of Forests within the Ministry of Agriculture, Water and Forestry is responsible for the forests. The Directorate is divided into two divisions: Forest Management and Forest Research. The Forestry Council includes Ministry staff and one person nominated by the Council of Traditional Leaders (Hailwa 2002)." | | |

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| **Nicaragua** | "The Ministry of Agriculture and Forests (MAGFOR) has authority over the forestry sector, working in concert with the National Forest Commission, the Ministry of the Environment and Natural Resources, and the Ministry of Promotion, Industry, and Trade (MIFIC)." | | "Under the 1997 Municipalities Law, local municipalities have the authority to develop, conserve, and control the use of natural resources, including timber and other forest products." | | |
| **Niger** | "The Forest Department has responsibility for forested areas, including reserves and non-reserves (Vogt et al. 2007)." | | "The 1993 Rural Code permits the devolution of the management and use of woodlands from the central government to communes, and in some cases to groups of local people through rural concessions (Delville 2000)." | | |
| **Nigeria** | "Nigeria's Constitution provides that the federal government has responsibility for protecting the country's forests." | "State-level forestry offices are authorized to enforce state forestry laws, but enforcement tends to be weak." | | | |
| **Panama** | "ANAM exerts state authority to regulate the use of natural resources by issuing licenses and permits." | | | | |
| **Paraguay** | "The two primary governmental institutions which regulate deforestation in the Chaco are the National Forestry Institute (INFONA) and the Secretariat of the Environment (SEAM)." | | | | |

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| **Peru** | "The Forest and Wildlife Law created the National Forest and Wildlife Service (SERFOR), as the national authority responsible for promoting the conservation, protection, growth and sustainable use of forests and wildlife." | | | | |
| **Philippines** | "The Department of Environment and Natural Resources (DENR) is responsible for the management, development and conservation of forest and grazing lands." | | | | |
| **Rwanda** | "The Ministry of Natural Resources (MINIRENA) has overall authority for the country's forestland and resources." | "District Councils grant these rights to selected entities (GOR Forest Law 2013)." | | | |
| **Senegal** | "The Directorate of Water, Forests, Hunting and Soil Conservation and the Directorate of National Parks within the Ministry of the Environment and Nature Protection are responsible for the planning, implementation, and monitoring of national forestry policy." | | "At local levels, a variety of governance bodies engage in forest management, including rural councils. In forest areas subject to the jurisdiction of the rural community, the rural council has authority to set quotas (Boye 2003; FAO 2005a; GOS 2004a; Diaw 2006). Despite a legal framework that allows for significant devolution of authority over forests and forest resources to local communities, most of the progress in devolution of authority has been in project areas supported by international NGOs and donors." | | |

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| **Sierra Leone** | "The Forestry Division of the Ministry of Agriculture, Forestry and Food Security (MAFFS) is responsible for forest management and biodiversity conservation." |  |  |  |  |
| **South Sudan** | "The Ministry of Agriculture and Forestry (MAF) has jurisdiction over the formulation of legislation and policy related to the use and management of South Sudan's forest resources." |  |  |  |  |
| **Sudan** | "The Ministry of Environment, Forestry and Physical Development is responsible for Sudan's forestlands." |  |  |  |  |
| **Tanzania** | "Tanzania's Ministry of Natural Resources and Tourism, and especially its Division of Forestry and Beekeeping (FBD), is responsible for the management and administration of the country's forests and forest resources. The Tanzania Forest Service (TFS) is a semi-autonomous government Executive Agency that was established through the Executive Agency Act (Cap. 245 Revised Edition 2009)." | "As a result of decentralization in the 1970s, district government offices manage a network of forest reserves. District authorities can issue licenses for timber harvesting in district forest reserves and for non-reserved forests and woodlands. District forest officers responsible for enforcement report to local district authorities as opposed to the central level FBD. Under the Local Government (District) Authorities Act, 1982, district authorities are responsible for maintenance of forests and for the prevention of soil erosion and desertification (GOT Forest Act 2002a; GOT 2009a)." | "Upon provision of an acceptable Village Forest Management Plan (VFMP), control and ownership of all the forest resources devolves to the village government. This gives communities the right to harvest and sell timber and forest products, as well as to undertake patrols (including arresting and fining offenders) to keep out illegal users." |  |  |

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| **Thailand** | "The Ministry of Natural Resources and the Environment (MNRE) is responsible for: assessing the country's natural resources; providing for the protection and sustainable use of the natural resources; and developing plans for equal benefit-sharing." | | | | |
| **Uganda** | "The National Forestry Authority, established in 2004, is an autonomous body with a mission to "[m]anage Central Forest Reserves on a sustainable basis and to supply high quality forestry-related products and services…" The National Forestry Authority and the military (Uganda People's Defense Force) launch joint patrols to curb illegal activities and enforce the law in Central Forest Reserves." | "The District Forestry Services under the Local District Administration are responsible for forestry extension (although forestry extension is technically part of the National Agricultural Advisory Services extension under the Ministry of Agriculture Animal Industries and Fisheries)." | | | |
| **Vietnam** | "Most forest-related administration and management falls under the Directorate of Forestry of the Ministry of Agriculture and Rural Development (MARD). MARD develops forest policy and provides oversight and guidance for its implementation. Forest protection at a provincial level falls to the | "The Law on Forest Protection and Development provides that the Ministry of Public Security, the National Ministry of Defense and the Ministry of Natural Resources and Environment shall collaborate with MARD at the district and provincial levels to implement forest policy. The number of agencies involved along with the highly decentralized nature of governing agencies has led to weak and ineffective | | | |

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| | provincial Departments of Agriculture and Rural Development (World Bank 2010a; World Bank 2010b; GOV Decree 119/2006/ND-CP 2006a)." | enforcement of forestry laws as well as uneven enforcement across regions (World Bank 2010a)." | | | |
| **Zambia** | "The Ministry of Lands, and Natural Resources (MLNR) has overall responsibility for forest resources in Zambia." | "The Forestry Department, under the Ministry of Lands and Natural Resources, is the government agency charged with administering and monitoring of forest resources. The Forestry Department has a presence in all nine provinces and in every district." | | | |
| **Zimbabwe** | "The Ministry of Environment and Tourism is in charge of forest management through the Forestry Commission, the Department of Natural Resources, and the Department of National Parks and Wildlife Management." | "Commercial timber extraction in communal areas is overseen by the Rural District Councils (RDCs). Based on a forest inventory approved by the Forestry Commission, an RDC may call for commercial tenders for exploitation, which also requires an environmental assessment. Ten percent of the fees collected from the winning concessionaire are given to local communities to be used for public and social services in the community (Shumba 2001b)." | | | |

## Supplementary Materials B

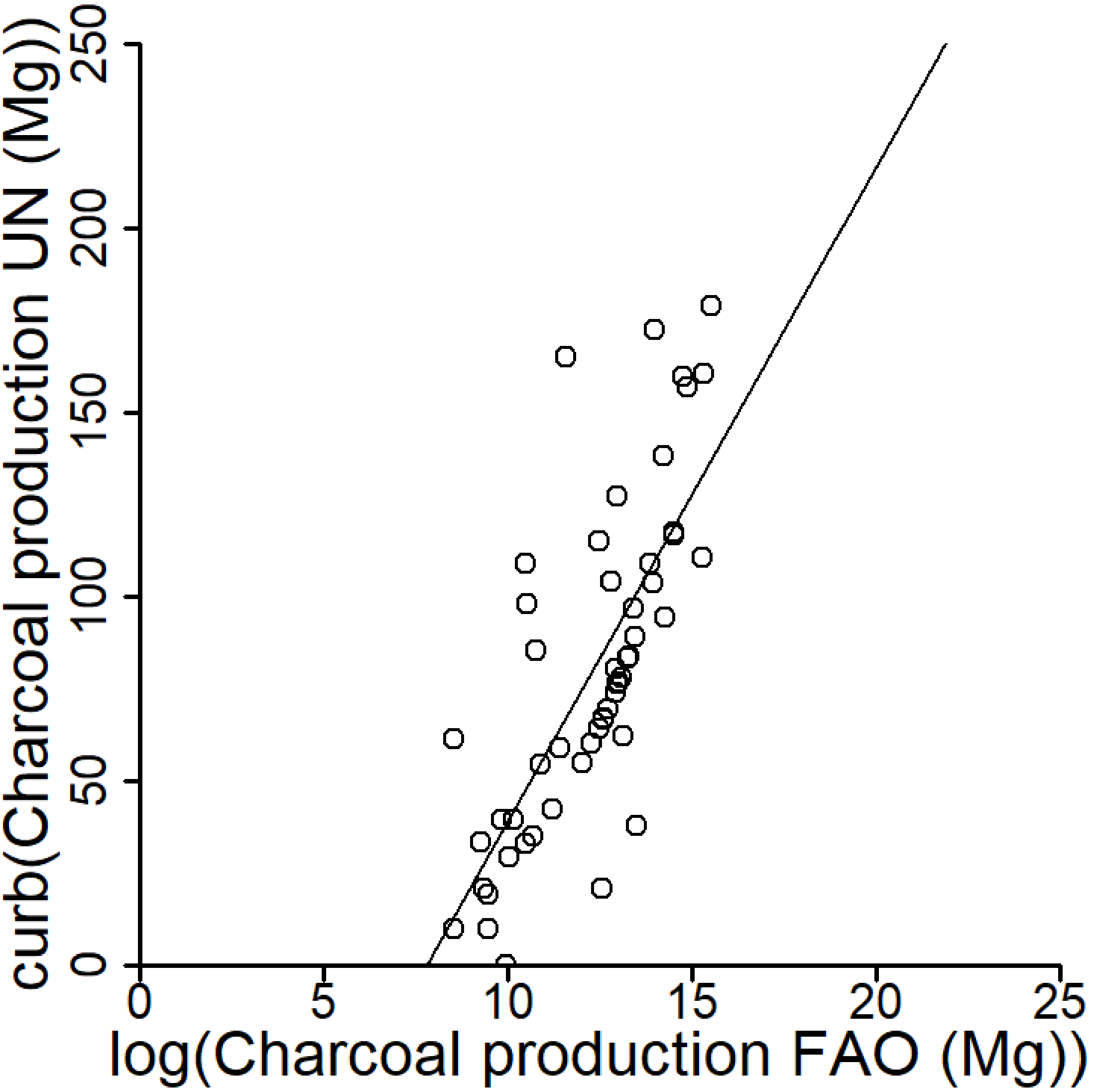

**Figure B1.** The relationship between the charcoal production data from the UN and the charcoal production data from FAO. Because the data was skewed, we cube transformed charcoal production data of the UN and log transformed charcoal production data of FAO, to better visualize their relationship. ($R^2 = 0.53$, $F_{(1,52)} = 61.4$, $P = 2.3 \times 10^{-10}$).

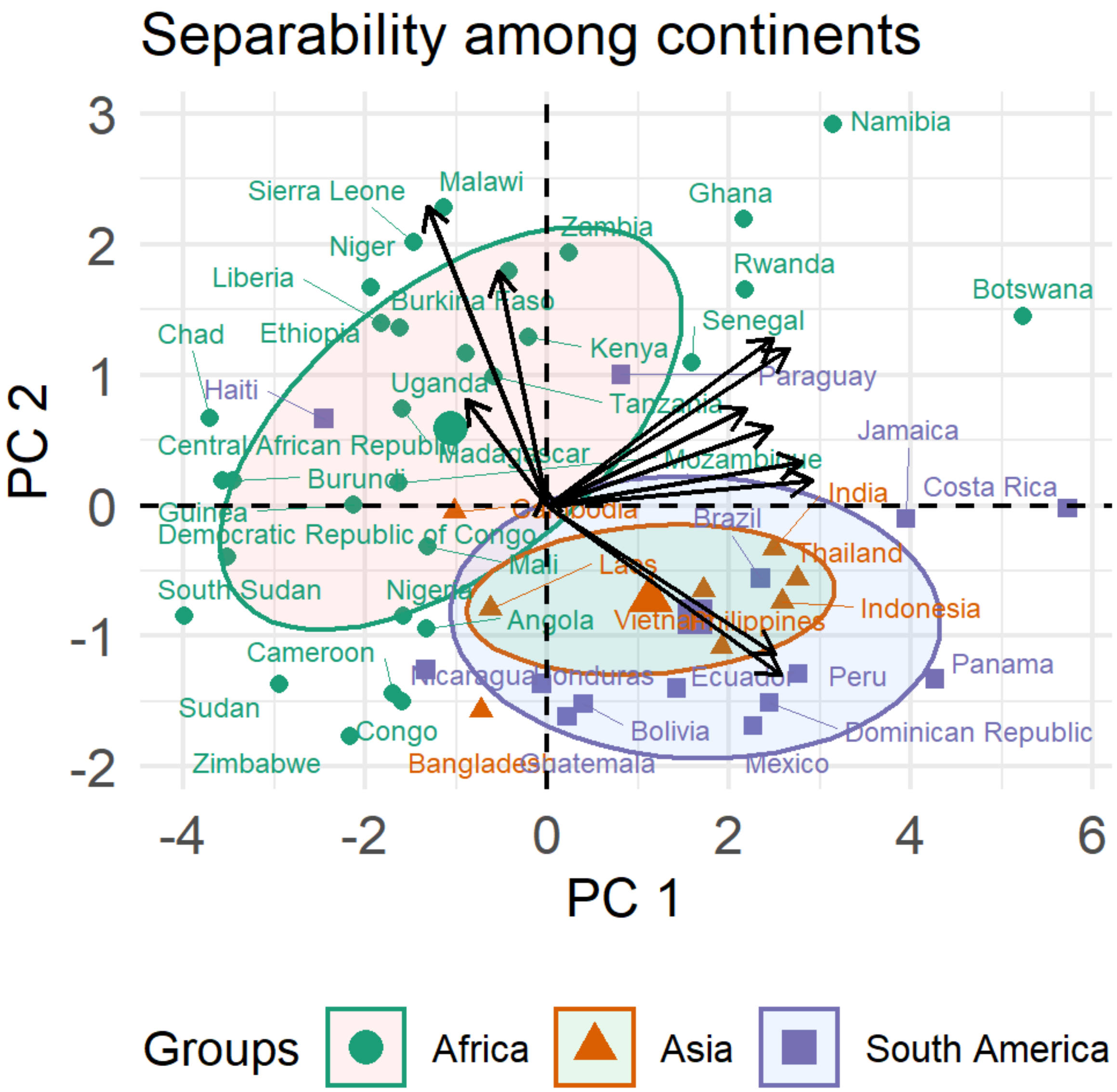

**Figure B2.** Overview figure of the same Principal Component Analysis (PCA) of Figure 3. We have removed one outlier (Ivory Coast) to provide a better visualization. The countries (points) have been colored based on the continent they originate from (i.e., the African, Asian and South American continent). The PCAs include charcoal production per capita (Charcoal) for FAO and UN data, deforestation rate, development indicators (GNI and HDI), and governance richness. WGI governance quality indicators, included Voice and Accountability (GQ_VaA), Political Stability (GQ_PS), Government Efficiency (GQ_Eff), Regulatory Quality (GQ_RQ), Rule of Law (GQ_RoL), and Corruption control (GQ_Cor) (See Table 1 for an explanation of each development and governance quality indicator and why it is included in the analysis). We calculated governance richness (GovRichness) of the entire governance system per country by summing the number of governing bodies with rights of tenure and enforcement.

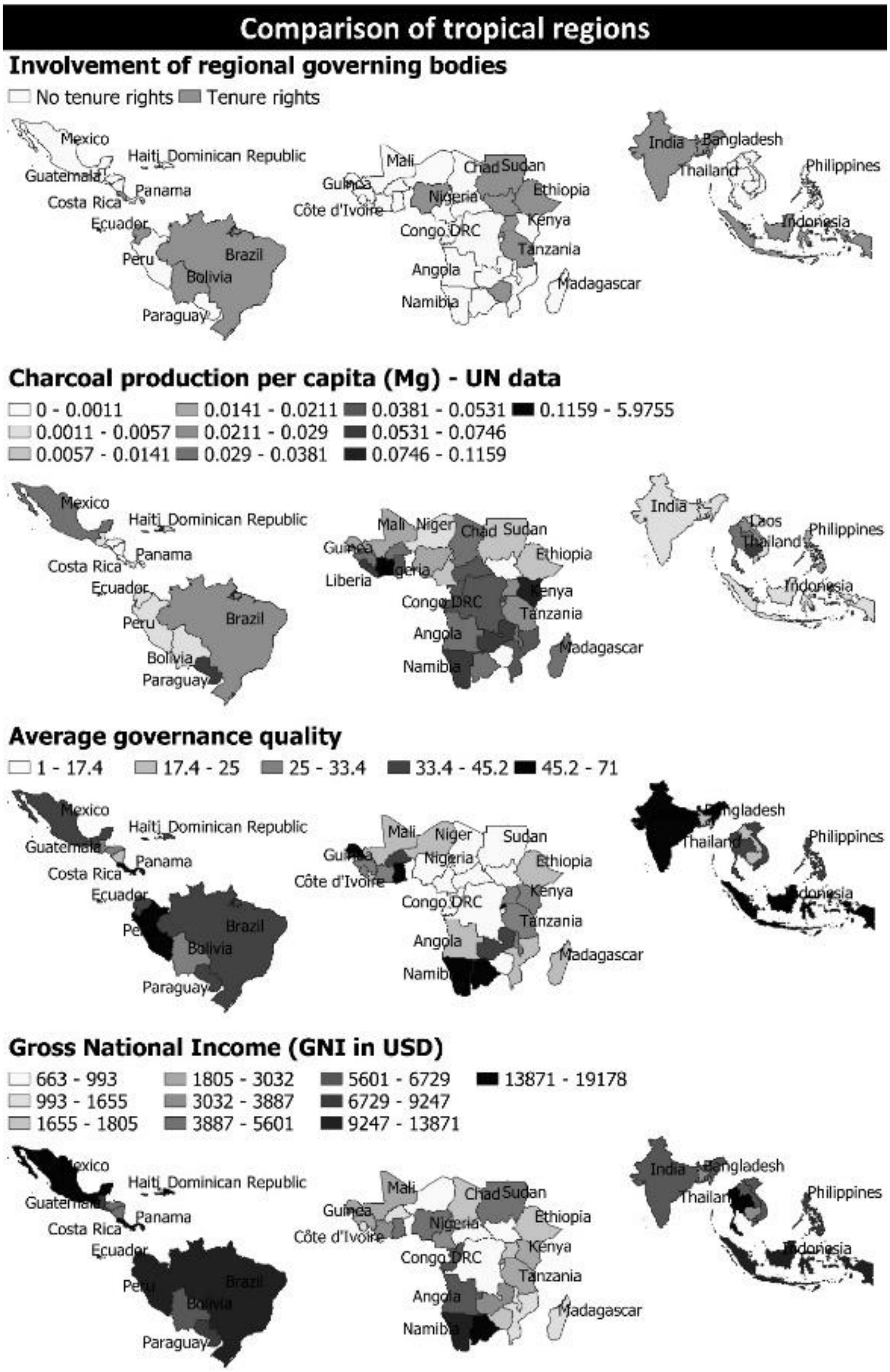

**Figure B3.** A spatial overview of (i) the countries that provide rights of tenure to regional governing bodies (along with other governing bodies such as national, local and/or individual governing bodies) based on USAID Country Reports on tenure rights, (ii) the charcoal production per citizen in Mg based (UN-data), (iii) the average governance quality based on the mean of the World Governance Indicators (WGI) of the World Bank, and (iv) Gross National Income (GNI in USD) of the World Bank. This allows for a comparison of regions and the detection of patterns that can be used to explain our results.

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At the beginning of my PhD I faced mental struggles, like many PhD students face and continue to face (Evans *et al* 2018). Thanks to the help and support of Emilia Vasella of the Psychologische Beratungsstelle of University of Zurich (UZH), I was able to process them. This process launched me on a journey to learn more about myself and mental health, which overall has made me an increasingly stronger and more resilient person. I am very grateful to Emilia Vasella for catalyzing and guiding me in this process.

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This PhD has been an incredibly valuable experience, which not only provided me the opportunity to contribute to science and to a certain extent policy making, but also allowed me to grow as a person.