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

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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 (a) develop a stylized model that simulates feedbacks between forest biomass and charcoal production, and (b) 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. All pathways 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 et al 2014, Baumert et al 2016, FAO 2017, Agyei et al 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...
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:

(a) 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).

(b) 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).

(c) 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 modelling studies have examined the role of interventions and their effects in charcoal systems (Robinson et al. 2012). For example, modelling a transition towards community forest management in South-West Cameroon showed a positive influence on charcoal producer revenues (Akoa et al. 2007). 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 (a) whether a system transition results in a change in forest and charcoal biomass dynamics and (b) if the timing of transition influences these dynamics.

2.1. Model environment

We considered an area of 10 000 ha and used long-term simulations (1000 years) to assess the potential for steady social-ecological system states to emerge (figure 1). We simulated 1000 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, ensuring availability of sufficient woody biomass for multiple people to produce charcoal simultaneously. In private systems, charcoal is produced from plantation biomass. We assumed that plantation biomass already exists within our model area, complementary to natural forests. We assumed that 20% (2000 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 (available online at stacks.iop.org/ERL/16/034009/mmedia) 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
Figure 1. A stylized charcoal model, which considered an area of 10 000 ha of which 5000 ha was forested at the initial model condition. All relationships are based on literature. Here, + = 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.

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  
Plantation: 367 600 Mg |
| $B_c$ (initial value) | Charcoal biomass (Mg) | 1260 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$^{-1}$  
Private: 0.043 year$^{-1}$ |
| $m_p$ | Harvesting rate in private systems (year$^{-1}$) | 100 000 Mg year$^{-1}$  
73 100 Mg 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$^{-1}$  
Plantation: 0.0426 year$^{-1}$ |
| $x$ | The production capacity/demand level at which half of the maximal harvest is reached (Mg year$^{-1}$) | 2517 Mg year$^{-1}$ |
| $K$ | Carrying capacity of natural forests and plantations (Mg) | Forest: 1 949 000 Mg  
Plantation: 416 000 Mg |
| $c$ | Carbonization efficiency of earth-mound kilns | 0.19 |
| $\delta_p$ | Depreciation rate of charcoal production (year$^{-1}$) | 0.019 year$^{-1}$  
1 year |
| $n$ | Population growth rate (year$^{-1}$) | 0.019 year$^{-1}$  
1 year |

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 centres 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:

\[
\frac{dB_f}{dt} = G - H
\]  \(1\)

\[
\frac{dB_c}{dt} = cH - (\delta_p + n) B_c.
\]  \(2\)

In equation (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 equation (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 (equation (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):

\[ G = gB_t \left( 1 - \left( \frac{B_t}{K} \right) \right) \]  

(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 (equation (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 centres 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 modelled production capacity as:

\[ P = \frac{DB_t^2}{(\nu^2 + B_t^2)} - \frac{B_t}{q} \]  

(4)

where \( P \) is the production capacity of charcoal (Mg year\(^{-1}\)), \( D \) is demand (Mg year\(^{-1}\)), \( \nu \) is the forest biomass harvested 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 modelled forest biomass harvest in open access systems as:

\[ H = \frac{mP^2}{(x^2 + P^2)} \]  

(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 and 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% 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 modelled biomass harvesting for charcoal production in communal management as:

\[ H_c = \frac{m_cB_tP^2}{(x^2 + P^2)} \]  

(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:

\[ H_p = \frac{m_p B_t \left( D - \frac{H}{4} \right)^2}{(x^2 + D^2)} \]  

(7)

where \( H_p \) 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 modelled different trajectories with varying demand (10 Mg year\(^{-1}\)–100 000 Mg year\(^{-1}\)), with light grey trajectories indicating high demand and dark grey 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 1000 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 100–200 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 1000 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 >1000 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 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 four steps spread over 50 years on forest and charcoal biomass for varying demand levels (10–100 000 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 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 >1000 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).
Instant transition in charcoal production systems after 20 years

Figure 2. Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of demand (10–100 000 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 grey tones, from light grey 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 1260 Mg (see supplementary materials A of this article).

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 figures 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 open access systems that experience high levels of demand at the start of the simulation (>60 000 Mg year$^{-1}$). Restoration of
Gradual system transitions

Figure 3. Tropical forest biomass and charcoal biomass levels over time in response to charcoal production under different levels of demand (10–100 000 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 grey tones, from light grey for low demands to black for high demands. A gradual transition from an initially open access system after 20 years is simulated in 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 1260 Mg (see supplementary materials A of this article).

forest biomass commences only after 800 years upon a demand reduction of 50 Mg year\(^{-1}\), while it takes \(\frac{1}{2}\) that time (400 years) when demand is reduced by 100 Mg year\(^{-1}\), and \(\frac{1}{4}\) 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 continue for more than 1000 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 1000 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 Schaafsma et al (2014), Baumert et al (2016) and Woollen et al (2016). 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 declines 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, causing the system to stabilize 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.
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 10–100 000 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 1260 Mg (see supplementary materials A of this article).

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 10–100 000 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 1260 Mg (see supplementary materials A of this article).

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). Evidence suggests that privatization may combat deforestation (Koyuncu and Yilmaz 2013). However, at present, many
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 10–100,000 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).

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 researchers 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% and 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 indicates 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 (Brown and Lugo 1984, Hofstad 1997, Bonner et al 2013). 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.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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References

Agyei F K, Hansen C P and Acheampong E 2018 Profit and profit distribution along Ghana’s charcoal commodity chain Energy Sustain. Dev. Sustain. Dev. 47 62–74
Ahrends A, Burgess N D, Milledge S A H, Bulling M T, Fisher B, Smart J C R, Clarke G P, Mhoro B E and Lewis S L 2010 Predictable waves of sequential forest degradation and biodiversity loss spreading from an African city Proc. Natl Acad. Sci. 107 14556–61
Akoa A, Olschewski R and Lescuyer G 2007 Economic Analysis of Community Forest Projects in Cameroon

Ameha A, Mulugeta H O and Lemenih M 2014 Participatory forest management in Ethiopia: learning from pilot projects Environ. Manage. 53 638–54
An L 2012 Modeling human decisions in coupled human and natural systems: review of agent-based models Ecol. Modell. 229 25–36
Azar C and Larson E D 2000 Bioenergy and land-use competition in Northeast Brazil Energy Sustain. Dev. 4 64–71
Bailis R 2009 Modeling climate change mitigation from alternative methods of charcoal production in Kenya Biomass Bioenergy 33 1491–502
Baumert S, Luz A C, Fisher J, Vollmer F, Ryan C M, Patenaude G, Zorrilla-Miras P, Artur L, Nhantumbo I and Macqueen D 2016 Charcoal supply chains from Mabalane to Maputo: who benefits? Energy Sustain. Dev. 33 129–38
Bonner M T L, Schmidt S and Shoo L P 2013 A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations For. Ecol. Manage. 291 73–86
Broto V C, Baptista I, Kirchner J, Smith S and Alves S N 2018 Energy justice and sustainability transitions in Mozambique Appl. Energy 228 645–55
Brouwer R and Magane D M 1999 The charcoal commodity chain in Maputo: access and sustainability South. African For. J. 185 27–34
Brown S and Lugo A E 1984 Biomass of tropical forests: a new estimate based on forest volumes Science 223 1290–3
Carvalho T H and Bacha C J C 2010. Analysis of the structure and location of charcoal production in Brazil—time period from 1980 to 2008 50th European Congress of the Regional Science Association Int. (ERSA2010) pp 1–23
Chidumayo E N and Gumbo D J 2013 The environmental impacts of charcoal production in tropical ecosystems of the world: a synthesis Energy Sustain. Dev. 17 86–94
Chingaipe B, Mwabumba L, Missanje E and Sengenimalunje T 2015 Effectiveness of local institutions in sustainable management of forests in selected communities in Dedza, Malawi J. Basic Appl. Res. Int. 12 2395–3446
Dagnachew A G, Hof A F, Lucas P L and van Vuuren D P 2020 Scenario analysis for promoting clean cooking in Sub-Saharan Africa: costs and benefits Energy 192 116641
FAO 2017 The Charcoal Transition: Greening the Charcoal Value Chain to Mitigate Climate Change and Improve Local Livelihoods (Rome: Food and Agriculture Organization of the United Nations)

Gautier D, Hauttididier B and Gazzulli L 2011 Woodcutting and territorial claims in Mali Geoforum 42 28–39
Ghate R and Nagendra H 2005 Role of monitoring in institutional performance: forest management in Maharashtra, India Conserv. Soc. 3 509–32

Ghilardi A, Tarter A and Bailis R 2018 Potential environmental benefits from woodfuel transitions in Haitian geospatial scenarios to 2027 Environ. Res. Lett. 1–11 035007

Gobeze T, Bekele M, Lemenih M and Kassa H 2009 Participatory forest management and its impacts on livelihoods and forest status: the case of Bonga forest in Ethiopia Int. For. Rev. 11 346–58
Guo L B, Sims R E H and Horne D J 2002 Biomass production and nutrient cycling in Eucalyptus short rotation energy forests in New Zealand. 1: biomass and nutrient accumulation Bioresour. Technol. 85 273–83
Heck V, Gerten D, Lucht W and Popp A 2018 Biomass-based negative emissions difficult to reconcile with planetary boundaries Nat. Clim. Change 8 151–5

Hillring B 2006 World trade in forest products and wood fuel Biomass Bioenergy 30 815–25

Hofstad O 1997 Woodland deforestation by charcoal supply to Dar es Salaam J. Environ. Econ. Manage. 33 17–32

Hofstad O and Araya M M 2015 Optimal wood harvest in Miombo woodland considering REDD+ payments—a case study at Kitulangalo forest reserve, Tanzania For. Policy Econ. 51 9–16

IEA 2014 World Energy Outlook 2014

Iiyama M, Neufeldt H, Njenga M, Serero A, Ndegwa G M, Mukunurinda A, Dobie P, Jamnadass R and Mowo J 2017 Conceptual analysis: the charcoal-agriculture nexus to understand the socio-ecological contexts underlying varied sustainability outcomes in African landscapes Front. Environ. Sci. 5 1–14

IPCC 2019 2019 Refinement to the 2016 IPCC guidelines for natural greenhouse gas inventories: chapter 4 forest land Forestry 4 1–29

Ishengoma R C, Katani J Z, Abdallah J M, Haule O, Deogratias K and Olomi J S 2016 World Energy Outlook 2014

Kilosa district harvesting plan

Kojima M 2011 The Role of Liquefied Petroleum Gas in Reducing Energy Poverty

Koyuncu C and Yilmaz R 2013 Deforestation, corruption, and private ownership in the forest sector Qual. Quant. 47 227–36

Laan T, Beaton C and Presta B 2010 Strategies for reforming fossil-fuel subsidies: practical lessons from Ghana, France and Senegal

Leujeune G, Ansay F, van Geit M and Luusenga T 2015 ECOnakala: Meeting energy needs, fighting poverty and protecting the forests of the Virunga National Park in North Kivu (DRC)

Luoga E J, Witkowski E T E F and Balkwill K 2000 Economics of charcoal production in Miombo woodlands of eastern Sub-Saharan Africa for: Energy and the Environment: Report of the Massachusetts Cabinet on Energy and the Environment 1999
Tanzania: some hidden costs associated with commercialization of the resources Ecol. Econ. 35 243–57

Mwampamba T H 2007 Has the woodfuel crisis returned? Urban charcoal consumption in Tanzania and its implications to present and future forest availability Energy Policy 35 4221–34

Mwampamba T H 2018 Incorporating ecohydrological processes into an analysis of charcoal-livestock production systems in the tropics: an alternative interpretation of the water-energy-food nexus Front. Environ. Sci. 6 1–15

Mwampamba T H, Ghilardi A, Sander K and Chaix K J 2013 Dispelling common misconceptions to improve attitudes and policy outlook on charcoal in developing countries Energy Sustain. Dev. 17 73–85

Ostrom E 2009 A general framework for analyzing sustainability of social-ecological systems Science 325 419–23

Piketty M, Wichert M, Fallot A and Aimola L 2009 Assessing land availability to produce biomass for energy: the case of Brazilian charcoal for steel making Biomass Bioenergy 33 180–90

Pinto R G D, Szklo A S and Rathmann R 2018 CO2 emissions mitigation strategy in the Brazilian iron and steel sector—from structural to intensity effects Energy Policy 114 380–93

Poteete A R and Ribot J C 2011 Repertoires of domination: decentralization as process in Botswana and Senegal World Dev. 39 439–49

Robinson E J Z, Albers H J and Lokina R B 2012 Improving forest management in Tanzania: understanding patterns of access rights, investments, and enforcement EFD Policy Br (https://doi.org/10.2307/resrep14825)

Santos M J, Dekker S C, Daigojlu V, Braakhekke M C and van Vuuren D P 2017 Modeling the effects of future growing demand for charcoal in the tropics Front. Environ. Sci 5 28

Schaafsma M et al 2014 The importance of local forest benefits: economic valuation of non-timber forest products in the eastern Arc mountains in Tanzania Glob. Environ. Change 24 295–305

Schure J, Levang P and Wiersum K F 2014 Producing woodfuel for urban centers in the Democratic Republic of Congo: a path out of poverty for rural households? World Dev. 64 1–11

Solow R M 1956 A contribution to the theory of economic growth Q. J. Econ. 65–94

Sonter I J, Barrett D J, Moran C J and Soares-filho B S 2015 Carbon emissions due to deforestation for the production of charcoal used in Brazil's steel industry Nat. Clim. Change 5 359–63

Specht M J, Pinto S R R, Albuquerque U P, Tabarelli M and Melo F P L 2015 Burning biodiversity: fuelwood harvesting causes forest degradation in human-dominated tropical landscapes Glob. Ecol. Conserv. 3 290–9

Stephens S and Wagner M R 2007 Forest plantations and biodiversity: a fresh perspective J. For. 105 307–13

Syampungani S, Tigabu M, Matakala N, Handavu F and Oden P C 2017 Coppicing ability of dry Miombo woodland species harvested for traditional charcoal production in Zambia: a win–win strategy for sustaining rural livelihoods and recovering a woodland ecosystem J. For. Res. 28 549–56

UN U N S D 2019 Energy Statistics Database

Vollmer F, Zorrilla-Miras P, Baumert S, Luz A C, Woollen E, Grundy I, Artur L, Ribeiro N, Mahamane M and Patenaude G 2017 Charcoal income as a means to a valuable end: scope and limitations of income from rural charcoal production to alleviate acute multidimensional poverty in Mabalane district, southern Mozambique World Dev. Perspect. 7–8 43–60

Woollen E, Ryan C M, Baumert S, Vollmer F, Grundy I, Fisher J, Fernando J, Luz A, Ribeiro N and Lisboa S 2016 Charcoal production in the Mopane woodlands of Mozambique: what are the trade-offs with other ecosystem services? Phil. Trans. R. Soc. B 371 1–14

Schaafsma M et al 2014 The importance of local forest benefits: economic valuation of non-timber forest products in the eastern Arc mountains in Tanzania Glob. Environ. Change 24 295–305

Schure J, Levang P and Wiersum K F 2014 Producing woodfuel for urban centers in the Democratic Republic of Congo: a path out of poverty for rural households? World Dev. 64 1–11

Solow R M 1956 A contribution to the theory of economic growth Q. J. Econ. 65–94

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Stephens S and Wagner M R 2007 Forest plantations and biodiversity: a fresh perspective J. For. 105 307–13

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UN U N S D 2019 Energy Statistics Database

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Woollen E, Ryan C M, Baumert S, Vollmer F, Grundy I, Fisher J, Fernando J, Luz A, Ribeiro N and Lisboa S 2016 Charcoal production in the Mopane woodlands of Mozambique: what are the trade-offs with other ecosystem services? Phil. Trans. R. Soc. B 371 1–14

Schaafsma M et al 2014 The importance of local forest benefits: economic valuation of non-timber forest products in the eastern Arc mountains in Tanzania Glob. Environ. Change 24 295–305

Schure J, Levang P and Wiersum K F 2014 Producing woodfuel for urban centers in the Democratic Republic of Congo: a path out of poverty for rural households? World Dev. 64 1–11

Solow R M 1956 A contribution to the theory of economic growth Q. J. Econ. 65–94

Sonter I J, Barrett D J, Moran C J and Soares-filho B S 2015 Carbon emissions due to deforestation for the production of charcoal used in Brazil’s steel industry Nat. Clim. Change 5 359–63

Specht M J, Pinto S R R, Albuquerque U P, Tabarelli M and Melo F P L 2015 Burning biodiversity: fuelwood harvesting causes forest degradation in human-dominated tropical landscapes Glob. Ecol. Conserv. 3 290–9

Stephens S and Wagner M R 2007 Forest plantations and biodiversity: a fresh perspective J. For. 105 307–13

Syampungani S, Tigabu M, Matakala N, Handavu F and Oden P C 2017 Coppicing ability of dry Miombo woodland species harvested for traditional charcoal production in Zambia: a win–win strategy for sustaining rural livelihoods and recovering a woodland ecosystem J. For. Res. 28 549–56

UN U N S D 2019 Energy Statistics Database

Vollmer F, Zorrilla-Miras P, Baumert S, Luz A C, Woollen E, Grundy I, Artur L, Ribeiro N, Mahamane M and Patenaude G 2017 Charcoal income as a means to a valuable end: scope and limitations of income from rural charcoal production to alleviate acute multidimensional poverty in Mabalane district, southern Mozambique World Dev. Perspect. 7–8 43–60

Woollen E, Ryan C M, Baumert S, Vollmer F, Grundy I, Fisher J, Fernando J, Luz A, Ribeiro N and Lisboa S 2016 Charcoal production in the Mopane woodlands of Mozambique: what are the trade-offs with other ecosystem services? Phil. Trans. R. Soc. B 371 1–14